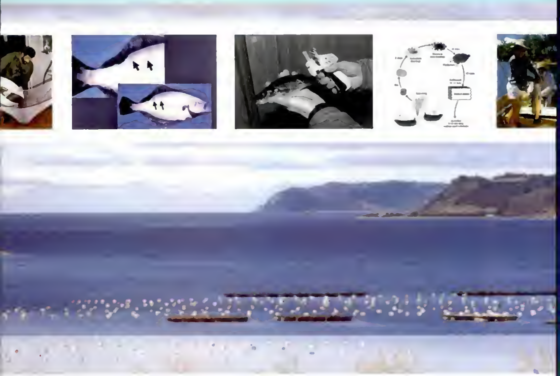
ISSN 0429-9345

FAO
FISHERIES
TECHNICAL
PAPER

429

Marine ranching



Cover photographs:
Insets: from authors' chapters. Main image. marine coastline central Chile. FAO/D. Bartley.

Marine ranching

FAO
FISHERIES
TECHNICAL
PAPER
429

Edited by
Devin M. Bartley
Inland Water Resources and Aquaculture Service
FAO Fisheries Department
Rome, Italy

and

Kenneth M. Leber
Mote Marine Laboratory
Sarasota, Florida
United States of America

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2004

This One
SRES-C3F-TE20

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

ISBN 92-5-104961-0

All rights reserved. Reproduction and dissemination of material in this information product for educational or other non-commercial purposes are authorized without any prior written permission from the copyright holders provided the source is fully acknowledged. Reproduction of material in this information product for resale or other commercial purposes is prohibited without written permission of the copyright holders. Applications for such permission should be addressed to:
Chief
Publishing Management Service
Information Division
FAO
Viale delle Terme di Caracalla, 00100 Rome, Italy
or by e-mail to:
copyright@fao.org

© FAO 2004

Preparation of this document

Under Component 6, "Assessment of sea ranching and marine hatchery enhancement", of the project Contribution of Fisheries to Food Security II (GCP/INT/643/JPN), international experts were selected to prepare five case studies and a summary on the use of hatchery-raised fish and invertebrates in increasing fishery production from marine and coastal areas.

Design and layout was performed by Daniela Scicchigno.

Abstract

With coastal fisheries in decline around the world, there is mounting concern about how long current sources of seafood can supply world needs. Governments, resource managers and those who make their livelihood on fishing are seeking better ways to improve fishing yields. Many seek greater emphasis on restocking and aquaculture-based stock enhancement as a way rapidly to replenish depleted fish stocks and increase fishery landings. This volume presents case studies that represent various scenarios and situations in using sea ranching and marine hatchery enhancement to generate income, re-establish fisheries and conserve aquatic biodiversity. The case studies include a global overview, an integrated development programme for marine stocking in Norway; stock enhancement of barramundi in Australia for recreational fisheries; restocking sea cucumbers in Pacific Islands; sturgeon stocking programmes in the Caspian Sea with an emphasis on Iran; and an assessment of stocking effectiveness of flounder in Miyako Bay, Japan, through a fish market census. The studies demonstrate that stocking can clearly work in some cases to increase fishery landings, but that economic success will depend on many factors such as the management system, survival, culture costs and how the resource is valued. Sea ranching technologies and strategies need more scientific development before stocking can be generally accepted as an economically effective fishery management tool in coastal regions.

Bartley, D.M.; Leber, K.M. (eds.)
Marine ranching.
FAO Fisheries Technical Paper. No. 429.
Rome, FAO. 2004. 213p.

Contents

Preparation of this document iii

Abstract iv

Marine and coastal stocking: global status and information needs 1
Abraham F. Born, Anton J. Immink and Devin M. Bartley

An integrated development programme for marine stocking: the Norwegian example 19
Terje Svåsand, Ann-Lisbeth Agnalt, Ove T. Skilbrei, Jørgen Borthen and Tor Heggberget

Stock enhancement of barramundi in Australia 73
D. J. Russell and M. A. Rimmer

The restocking of sea cucumbers in the Pacific Islands 109
Stephen C. Battaglene and Johann D. Bell

Sturgeon stocking programme in the Caspian Sea with emphasis on Iran 133
Hossein Abdolhay

Flounder stock enhancement in Miyako Bay, Japan 171
Hiroyuki Okouchi, Shuichi Kitada, Akio Iwamoto and Tatsuhiro Fukunaga

Summary of case studies of the effectiveness of stocking aquacultured fishes and invertebrates to replenish and enhance coastal fisheries 203
Kenneth M. Leber

Marine and coastal stocking: global status and information needs

Abraham F. Born
E. Faes Straat 130B, 1090 Brussels, Belgium

Anton J. Immink
Stirling Aquaculture, Institute of Aquaculture, University of Stirling, Stirling FK9 4LA, The United Kingdom of Great Britain

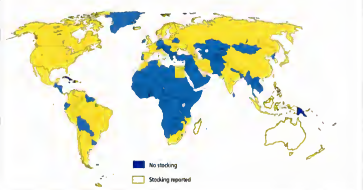
Devin M. Bartley
Fisheries Department, FAO, Viale delle Terme di Caracalla, 00100 Rome, Italy

ABSTRACT

Production from many of the world's fisheries has remained constant over recent years and is not expected to keep up with a growing human population's demands for fishery products. In addition, environmental degradation and poor fisheries management have caused several of the world's fisheries to decline and even collapse. Stocking of early life history stages of fish is one fishery management option that is being used to address the need for continued production from marine and coastal areas.

We reviewed information that Members provided to the Food and Agriculture Organization of the United Nations (FAO) and scientific and "grey" literature to assess the status of stocking programmes worldwide and to assess the information available to evaluate such programmes (Figure 1). Analysis revealed, *inter alia*, that between 1984 and 1997, 64 countries reported the stocking of species that spend a part of their life in marine and coastal areas. Japan is the world leader in marine stocking, however, many of the stocking programmes are experimental or pilot scale. Review of the literature uncovered only a fraction of the global activity in stocking, partly because many government programmes are not published. Conversely, several countries that

FIGURE 1. Countries with reported Marine Stocking



document their stocking programmes in the scientific literature did not report any stocking information to FAO. Many believe that stocking will become an increasingly important fishery management tool in the future. However, the practice must be evaluated and monitored accurately.

Worldwide, 64 countries reported some activity in marine and coastal stocking with approximately 180 different species being released of which 46 species are confined to marine environments. The species used are generally not widespread, except for several salmonids. Europe and North America have relatively the highest number of countries that reported marine and coastal stocking, Africa and Latin America show a lower effort with an intermediate position for Asia and Oceania.

Currently, inconsistencies in reporting and monitoring hinder accurate assessment of many stocking programmes. Standardized nomenclature and reporting format are suggested that will facilitate data reporting and enable resource managers and development agencies to evaluate more accurately the role of stocking programmes in marine and coastal areas.

INTRODUCTION

Production from many of the world's fisheries has remained constant over recent years and is not expected to keep up with a growing human population's demands for fishery products. In addition, environmental degradation and poor fisheries management have caused several of the world's fisheries to decline and even collapse. Stocking[1] of early life history stages of fish is one fishery management option that is being used to address the need for continued production from marine and coastal areas.

Hatchery enhancement of marine and coastal stocks[2] has been criticized on the grounds that it is not effective, not economically feasible, prevents alternative solutions from being implemented (sound fishery management, habitat restoration) and that it endangers native aquatic resources (genetic interactions, competition) (Bartley, 1996). Stocking is one of the options to augment, maintain or restore fisheries production and it should preferably be accompanied by sound fisheries management (e.g. minimum mesh sizes, closed seasons etc.) to achieve it is maximum benefit. A good example is the recovery of red drum stocks in Texas through the initiation of an overall recovery plan including stocking and fisheries regulations (McCartey *et al.*, 1993). Unfortunately, fisheries regulations are often difficult to enforce and as a result stocking is being used in situations of sub-optimal fishery management and over-exploitation. It has been adopted by Governments as a clearly visible measure to support fisheries without knowing the exact causes for decreasing capture fisheries. In these situations stocking programmes may fail and the conclusion is drawn that marine stocking is not working.

Marine stock enhancement has a history of controversy, partly because of lack of proper monitoring and data recording. Given the renewed interest in marine stock enhancement in the last 20 years and it is history of mixed results it is important to keep track of the trends and developments. Governments and development agencies are becoming more critical to stock enhancement and it will be important to provide them with sufficient information regarding the status of this management option. This is even more important because many believe that stocking will become an increasingly important fishery management tool.

---

[1] The terms (sea) ranching, marine stocking, marine stock enhancement and hatchery enhancement have all been used to describe release of hatchery-raised animals into the wild. For the purpose of this document no distinction is made between these terms, although subtle differences in meaning do exist.

[2] For the purpose of this paper we use the term "marine stocking" for stock enhancement of both marine and coastal stocks.

We reviewed information that Members provided to FAO and scientific and "grey" literature to assess the status of stocking programmes worldwide and to assess the information available to evaluate such programmes. Hatchery Production Statistics provided by Member countries of FAO have only recently become available within FAO. We present these data and make recommendations for further improvement of reporting and monitoring of stocking programmes in marine and coastal environments.

DATA RESOURCES AND DATA PROCESSING

FAO's Hatchery Production Data are provided by its Members on the basis of a questionnaire issued by the FAO Fisheries Statistical Division. These data have recently been compiled and organized by A. Immink. The data are segregated by species (including various life-stages), country, year and release environment (into controlled environments – i.e. for aquaculture, or into the wild – i.e. for stock enhancement) and cover the period 1984–1997. Production figures are mostly given in numbers. For the purpose of this contribution, releases into the wild were analysed excluding releases for aquaculture purposes. Data from landlocked countries were excluded.

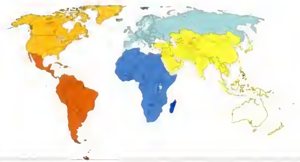
As a second source of information literature in the Aquatic Sciences and Fisheries Abstracts (ASFA) was used. This database was searched for information on stock enhancement (stocking, ranching) in marine and brackish water environments. The selected references (1 173 in total) were organized in a spreadsheet and a list of species appearing in the references was prepared. First selection of references was based on this species list. Only the species that spend at least a part of their lifecycle in marine environments were included. Species confined to brackish-fresh (for example tilapia) and freshwaters were excluded and a part of the species that live in all three environments were excluded: (i) if never used for aquaculture in marine/brackish environments according to the FAO Aquaculture Statistics 1987–1996 (FAO, 1998): *Thymallus thymallus*, *Plecoglossus altevilus* and *Salvelinus fontinalis*; (ii) if known to be stocked in freshwater from scientific literature: *Coregonus peled* (reservoirs species). Information about species and their environment was taken from the FAO Database on Introductions of Aquatic Species and FishBase (Froese and Pauly, 1998). A list of species used in the analysis is given in Appendix 1. A total of 158 ASFA references were found relevant to marine and coastal stock enhancement.

TABLE 1. Countries reporting marine stocking by region

Region	Total number of countries reporting marine stocking	Number of countries reporting hatchery production to the FAO	Number of countries reporting stocking in the literature and ASFA
Europe	19	16	11
Asia and Oceania	23	19	7
Africa	9	9	0
North America	2	1	2
Latin America	11	11	0
All	64	56	20

Copyright material

FIGURE 2. Definitions of regions



GEOGRAPHIC COVERAGE OF MARINE STOCK ENHANCEMENT INFORMATION

Fifty six countries reported marine hatchery releases to FAO between 1984 and 1997. Additionally, eight more countries reported stocking practices and research in scientific literature only. Worldwide, 64 countries reported some activity in marine and coastal stocking, ranging from experimental research or large scale industrial releases as shown in Figure 1.

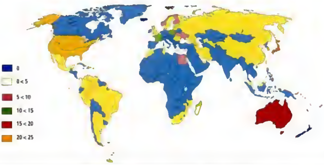
Marine stocking practices are not equally represented among regions as can be seen in Table 1 (for definition of the regions see Figure 2). Africa and Latin America do not have any relevant stocking examples in the ASFA literature, although stocking is practised in these regions as reported by hatchery production. In general, countries in developed regions (Europe, North America) contribute more scientific information to ASFA. Information in the less developed regions is probably more abundant in grey literature (project reports). In conclusion, many countries thatO have marine stocking programmes do not report these in scientific literature. Efforts should be made to explore information in unpublished reports and grey literature to obtain information for these countries.

To get a more balanced picture of the extent of marine stocking in the various regions, the countries that reported stocking are expressed as a percentage of all countries that are connected to marine environments including the Caspian and Black seas (i.e. excluding landlocked countries). Europe and North America have relatively the highest number of countries that reported marine stocking; Africa and Latin America show a lower effort with an intermediate position for Asia and Oceania. Worldwide, about one third of all countries with a connection to the sea report stock enhancement (Table 2).

TABLE 2. Relative importance of marine stocking by region

Region	Countries reporting marine stocking (A)	Countries with sea connection (B)	A/B
Europe	19	35	0.54
Asia and Oceania	23	61	0.38
Africa	9	41	0.22
North America	2	4	0.50
Latin America	11	42	0.26
All	64	183	0.35

FIGURE 3. Number of species reported to FAO as released into the wild



The number of species produced in hatcheries for release into marine and coastal environments as reported to FAO is given in Figure 3. More than ten different marine and coastal species are stocked in the United States, Republic of Korea (South Korea), Australia, Japan, Spain and Poland. For some countries the numbers are lower than we know from scientific literature. For example, in Japan over 80 species are reported to be reared for stock enhancement (Masuda and Tsukamoto, 1998) and various species are stocked in Canada despite the absence of hatchery production data for this country. However, the production figures give additional information about countries and species that are not reported in scientific literature. For example, Republic of Korea reports marine stocking of 21 species, but no accounts were found in the scientific literature. This information can be useful for further studies into the feasibility of marine stocking programmes.

Species that are stocked in two or more different countries are presented in Table 3. Species are divided into three groups: marine, marine-brackish and marine-brackish-fresh. In the first two groups, geographical distribution is limited to a maximum of four reporting countries. In the third group, rainbow trout, sea trout and Atlantic salmon are relatively widespread. It should however be noted that rainbow trout in many cases is stocked in freshwater environments and that the countries that practise stocking of sea going rainbow trout are probably overestimated. Sea trout and Atlantic salmon are species used for marine ranching with a large geographic range worldwide. In conclusion, species used in marine stocking are generally not widespread, except for some salmonids.

White seabass, lobsters and cod are reportedly stocked in only one/no country, e.g. cod in Norway, white seabass not reported. We have only included in Table 3 species that are stocked in at least two countries according to hatchery production data to prevent this table form being overly extensive. Table 3 could have been extended using information from the ASFA, but it is mainly to show that the species used for marine stocking are not widespread but only locally released except for salmonids. This is also why some species in Table 3 are different from those in Table 4. In the latter they are ranked according to production, in the former according to the number of countries in which they are stocked.

TABLE 3. Species reported to be stocked in two or more countries

Marine, 34 total	**Common name**	**Countries**
Strombus gigas	Queen conch	3
Pagrus major	Red seabream	3
Trochus niloticus	Topshell	2
Mithrax spinosissimus		2
Tridacna derasa	Giant clam	2
Paralichthys olivaceus	Japanese flounder	2
Puntazo puntazo		2
Marine–brackish, 24 total		
Penaeus monodon	Giant tiger prawn	4
Penaeus japonicus	Kuruma prawn	3
Sparus auratus	Gilthead seabream	2
Penaeus merguiensis	Banana prawn	2
Marine–brackish–fresh, 43 total		
Oncorhynchus mykiss	Raibow trout/steelhead	26
Salmo trutta	Sea trout	19
Salmo salar	Atlantic salmon	14
Coregonus lavaretus	Whitefish	7
Acipenser spp.	Sturgeons	7
Lates calcarifer	Barramundi	6
Salvelinus alpinus	Arctic char	5
Oncorhynchus kisutch	Coho salmon	4
Oncorhynchus tshawytscha	Chinook salmon	4
Oncorhynchus keta	Chum salmon	3
Coregonus spp.	Whitefish	3
Dicentrarchus labrax	European seabass	3
Oncorhynchus gorbuscha	Pink salmon	2
Plectroplites ambiguous		2
Mugil spp.	Mullets	2
Oncorhynchus masou	Masou salmon	2
Lampetrafluviatilis		2
Mugil cephalus	Grey mullet	2
Salvelinus spp.	Chars	2

Source: FAO hatchery production statistics.

In terms of production (numbers produced) the major stocked species are listed in Table 4. Japan and Republic of Korea produce various marine and brackish species such as Ezo scallop (*Patinopecten yessoensis*), Red seabream (*Pagrus major*), Japanese flounder (*Paralichthys olivaceus*) and Black porgi (*Acanthopagrus schlegeli*) in large quantities. Furthermore, Queen conch (*Strombus gigas*) is produced on a large scale in the Caribbean as well as Giant clam (*Tridacna maxima*) in Tonga. Various shrimps, scallop and the oyster *Crassostrea gigas* are released into marine-brackish environments. Of the species occurring in all environments, the salmonids (*Oncorhynchus* spp., *Salmo* spp.) and coregonids are extensively produced for stocking.

Table 4 indicates a large variation in the number of years for which data were reported for stocked species. For example stocking data from several years exist for the crab *Portunus trituberculatus*, Black rockfish (*Sebastes schlegeli*), and black porgy (*Oplegnatus faciatus*) from Republic of Korea and Japan and for salmonids and striped bass in the United States. Many species are however reported sporadically as illustrated in Figure 4. The number of species and countries with data for more than seven years are shown in Table 5 (38 species). The data indicate that for various salmonids, striped bass (*Morone saxatilis*), red seabream, Japanese flounder and the shrimp *Penaeus orientalis kishimouye* long-term enhancement programmes are carried out. However, the number of species with long data series is limited, indicating that many stocking programmes have been experimental rather than industrial and that data were not provided consistently to FAO.

TABLE 4. Major species in terms of hatchery production for release into natural environments

Species	Total no produced between 1984 and 1997	Average no. of years reported	No. of countries	Countries
Marine				
Patinopecten yessoensis	5 656 216 000	3	1	Japan
Pagrus major, Acanthopgrus schlegeli, Ebynnis japonica	105 019 000	2	1	Japan
Paralichthys olivaceus	55 878 000	2	1	Japan
Tridacna maxima	25 020 000	2	1	Tonga
Penaeus vannamei, P. stylirostris	22 500 000	1	1	Panama
Pagrus major	14 230 000	3	3	Japan, Republic of Korea, Taiwan Province of China
Seriola quinqueradiata, S. aureovitlata, S. dumerili	13 963 000	3	1	Japan
Portunus trituberculatus	9 361 000	7	1	Republic of Korea
Strombus gigas	5 700 000	1	3	Belize, Sao Tome, Turks & Caicos Islands
Paralichthys olivaceus	3 593 000	5	2	Japan, Republic of Korea
Sebastes schlegeli	2 739 000	7	1	Republic of Korea
Acanthopagrus schlegeli	1 009 000	9	1	Republic of Korea
Haliotis diversicolor aguatilis	889 000	2	1	Taiwan Province of China
Oplegnathus fasciatus	613 000	6	1	Republic of Korea
Marine-brackish				
Penaeus (orientalis) chinensis	1 370 000 000	1	1	China
Penaeus japonicus	366 327 501	3	4	Japan, Republic of Korea, Portugal, Taiwan Province of China
Scallop	165 937 000	3	1	USSR
Crassostrea gigas	160 140 000	3	1	Japan
Penaeus orentalis kishimouye	106 655 000	8	1	Republic of Korea
Penaeus monodon	26 316 000	1	5	Brunei, Republic of Korea, Mauritius, Seychelles
Penaeus merguiensis	16 925 800	1	1	Malaysia
Mugil incilis	15 468 000	3	1	Colombia
Sciaenops ocellatus	141 00 045	3	1	USA
Sparus auratus	7 620 000	1	3	Cyprus, Egypt, Portugal
Penaeus stylirostris	1 500 000	1	1	Panama
Sparus auratus, Dicentrarchus labrax	950 000	1	1	Cyprus

Table continues overleaf

TABLE 4. Major species in terms of hatchery production for release into natural environments *(continued)*

Species	Total no. produced between 1984 and 1997	Average no. of years reported	No. of countries	Countries
[illegible]				
Coregonus spp.	18 522 918 000	4	6	Finland, France, Russian Federation
Oncorhynchus gorbuscha	8 523 667 135	7	2	Chile, USA
Oncorhynchus keta	3 961 456 987	9	3	Chile, USA, Republic of Korea
Oncorhynchus mykiss	3 787 792 804	4	42	France, USA, South Africa, Finland, Iran, etc.
Salmo trutta	3 523 832 192	5	25	France, USA, Finland, Poland, etc.
Oncorhynchus tshawytscha	1 543 758 158	6	4	Australia, New Zealand, USA, Chile
Oncorhynchus nerka	1 489 348 103	14	1	USA
Acipenser spp.	1 016 164 800	4	7	Azerbaijan, Iran, Ukraine, Russian Federation, Georgia, France
Oncorhynchus kisutch	568 460 018	5	4	Chile, Cyprus, USA, France
Mugil cephalus, Liza ramada	526 500 000	6	1	Egypt
Salmo salar	337 348 663	5	25	Norway, USA, Finland, Iceland, Sweden, etc
Coregonus lavaretus	146 405 400	2	7	Estonia, Finland, Lithuania, Poland
Oncorhynchus spp.	137 446 735	2	1	USA
Morone saxatilis	125 937 206	14	1	USA

Source: FAO hatchery production statistics.

Tables 3 and 4 are based on the FAO hatchery production statistics. As shown in Table 6, some known released species are not reported to FAO, because (i) reports of member countries are incomplete; (ii) private sector and pilot-scale stocking efforts are not included because data are based on official government information. It should be noted that Table 6 does not include the many species stocked in Japan.

Note: Rainbow trout (*O. mykiss*) and other salmonids are stocked in fresh, brackish and marine environments. The data do not provide information about the release environment and may therefore be biased for these species.

FIGURE 4. Number of reported years per species

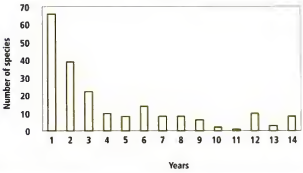


TABLE 5. Countries and species with long-term records (8–14 years) in the Hatchery Production Statistics

Country	Species
USA	*Morone saxatilis, Oncorhynchus clarki, O. gorbusha, O. keta, O. kisutch, O. mykiss, O. nerka, O. tshawytscha, S. salar, S. trutta, Acipenser brevirostrum*
Finland	*O. mykiss, Salmo salar, S. trutta*
Republic of Korea	*O. keta, Acanthopagrus schlegeli, Pagrus major, Paralichthys olivaceus, Penaeus orientalis kishimouye*
Latvia	*S. salar, S. trutta, O. mykiss*
Morocco	*O. mykiss, S. trutta*
Sweden	*S. salar, S. trutta*
France	*S. trutta, S. salar*
Iceland	*S. salar*
Georgia	*S. trutta*
Colombia	*O. mykiss*
Belgium	*O. mykiss*
Cyprus	*O. mykiss*

Note: Rainbow trout (*O. mykiss*) and other salmonids are stocked in fresh, brackish and marine environments. The data do not provide information about the release environment and may therefore be biased for these species.

TABLE 6. Stocked species not present in the Hatchery Production Statistics

Species	Common name	Countries	Remark
Alosa sapidissima	American shad	USA (Pennsylvania)	
Anadara broughtonii	Arkshell	Japan	
Atractoscion nobilis	White seabass	USA (California)	
Centropomus undecimalis	Common snook	USA (Florida)	
Chelonia mydas	Green sea turtle	Philippines	
Coryphaena hippurus	Common dolphinfish	USA (Hawaii)	Proposed
Gadus macrocephalus	Pacific cod	USA (Puget Sound), Japan	
Haiotis discus hannai	Ezo abalone	Japan	
Homarus americanus	Lobster	USA	
Homarus gammarus	Lobster	Norway, UK, USA (Maine)	
Lepidochelys kempi	Kemp's ridley turtle	USA	
Mercenaria mercenaria	Hard clam	USA (North Carolina, New York)	
Ophiodon elongatus	Ling cod	USA	Proposed
Panope abrupta	Geoduck clam	USA	
Paralichthys californicus	California halibut	USA (California)	
Pecten novaezelandiae	Scallop	New Zealand	
Platichthys flesus	Flounder	Denmark, Netherlands (1977)	
Pleuronectes platessa	Plaice	Denmark, Netherlands (1977)	
Polydactylus sexfilis	Pacific treadfin	USA (Hawaii)	
Portunus trituberculatus	Crab	Japan	
Pseudocaranx dentex	Striped jack	Japan	Proposed
Scophthalmus maximus	Turbot	Denmark	
Sparus aurata	Gilthead seabream	Tunisia (lagoons)	
Takifugu rubripes	Tiger puffer	Japan	Probably

An overall table with stocked species, the countries and source of information is given in Appendix 1 for further reference. We found 119 different species stocked for marine enhancement, of which 26 were in Japan. Assuming that another 60 species that are not included in the list are stocked in Japan (a total of 80 or more species for marine stocking in Japan), we arrive at a total of 180 species that have been stocked for marine and coastal enhancement. For some of these it is difficult to know the exact release environment and the list may therefore include species-country combinations that belong to inland stocking. Further analysis and improvement of this preliminary analysis will exclude these combinations. According to Moksness and Stoele (1997), in the Pacific, more than 30 fish species have been identified as part of a future sea ranching programme, and in the Atlantic fewer than ten. We have listed considerably more species, probably because we included not only the genuine marine and brackish species but also species that can be stocked from fresh to saline waters. If we only include those confined to marine environments, we find a total of 46 species that have been used for sea ranching.

THE NEED FOR STANDARDIZED NOMENCLATURE AND REPORTING FORMAT

With nearly 70 countries stocking approximately 180 species, it is clear that stocking projects represent a significant global activity in managing marine and coastal fisheries. Fishery managers and international development organizations have high expectations for stocking programmes:

- "Sea ranching provides one of the best possibilities for greatly increasing some fish and shellfish production..." – International Center for Living Aquatic Resources Management (ICLARM) press release, 1995.
- Kyoto Plan of Action calls for "...rapid transfer of technology and know-how in enhancement of inland and marine waters" – FAO/Japan Kyoto Conference, 1995.
- "Explore the potential ... to enhance ... fisheries ... through stock enhancement." – Australia's National Policy on Aquaculture.

On the other hand, serious concerns have been raised about the usefulness of marine stocking and its possible negative impacts on native fauna.

Not all scientists feel that stocking is an appropriate management option for fisheries management and many fishery managers realize that stocking alone will not be an effective means to manage fisheries:

- "Enhancement measures should be evaluated against other management measures... not only in terms of costs, productivity and catches but more importantly in relation to sustainability." (Kirkegaard, 1997);
- "Do not use artificial propagation as a substitute for precautionary measures..." (FAO, 1995b).
- "History has shown that a hatchery program can generate a broad base of public and political support in the total absence of any objective evidence that it actually works" (MacCall, 1989), but perhaps the title of Dr MacCall's paper is more telling: "Against marine fish hatcheries: ironies of fishery politics in the technological era".

The first prerequisite for objective evaluation of the pros and cons of stock enhancement is a sound information base including accurate information on the effectiveness and cost-effectiveness of stocking programmes to allow policy makers, fishery managers and conservationists to make informed decisions. In this respect, Article 9.2.4 of the FAO Code of Conduct for Responsible Fisheries calls on countries to "... establish appropriate mechanisms, such as databases and information networks to collect, share and disseminate data in order to have a responsible development of aquaculture, including culture-based fisheries in areas under national jurisdiction... (and) within transboundary aquatic ecosystems." (Article 9 FAO, 1995). Technical guidelines have been created to help implement the Code.

Unfortunateley, in practice it seems difficult to obtain accurate information on stock enhancement operations. The European Union is conducting a project, "Analysis of the environmental and economic impact of operations to reinforce the aquatic fauna of fresh waters for fishery purposes" which is essentially an evaluation of inland stocking programmes. It has been difficult to obtain accurate data on the scale and success of these operations (Ian Cowx, personal communication). If accurate data on inland stocking in Europe are difficult to obtain, gathering data on marine stocking in less developed areas would be expected to be even more problematic.

Currently, information on stocking and the results of stocking are scattered among government offices/publications, grey literature and academia and scientific literature. There is a need for stakeholders to work together to gather this information in an accessible format. The following suggestions are offered to move toward improving information in order to achieve more responsible stocking programmes.

- Improve reporting forms, e.g. FAO country questionnaires, and standardize terms;
- scientists and government resource/hatchery managers should work together to gather information and present it in an user-friendly format, this should include extracting existing data from grey literature;
- establish monitoring systems to judge accurately the cost/benefit (in monetary and non–monetary terms) of stocking programmes;
- promote awareness of the issues and controversies associated with stocking so that appropriate data can be gathered and disseminated to appropriate stakeholders;
- include stocking of inland waters and identify commonalities and differences between stocking inland and marine and coastal areas.

FAO is currently improving the collection of its hatchery production data. Although FAO has requested hatchery data from countries since it began collecting aquaculture data in 1984, the data have never been processed because of a lack of immediate interest from member countries. Over time this has led to gaps in the data some of which are now quite large (Figure 4, Appendix 1). FAO hopes, in collaboration witb national governments, to collate these non-reported data so that a more complete record is compiled. The FAO aquaculture questionnaire (on which these data are collected) is currently undergoing a process of revision, which should give clearer definitions and instructions for completion of the form. It is hoped that this new form, to be compiled in conjunction with national statistical agencies, will improve data submission. A public hatchery database is still some years away, but in the meantime we will strive to make current data collection more consistent. Hatchery data are important for governments to assess the efficiency of aquaculture production systems (what goes in should come out) and also to assess stocking programmes, not just for efficiency, but also for stock quality and sustainability.

It is our hope that the database presented here and groups of interested stakeholders, such as the WAS working group on Responsible Stock Enhancement, will help promote responsible stocking and implement elements of the Code of Conduct for Responsible Fisheries.

References

Bartley, D.M. 1996. Conservation of biological diversity in hatchery enhancement programmes. *In* di F. Castri & T. Younès, eds. *Biodiversity, science and development: towards a new partnership*, pp. 424–438. Wallingford, UK, CAB International.

FAO. 1995a. *Code of conduct for responsible fisheries.* FAO, Rome.

FAO. 1995b. *Precautionary approach to fisheries. Part 1: guidelines on the precautionary approach to capture fisheries and species introductions.* FAO Fisheries Technical Paper 350/1. FAO, Rome.

FAO. 1998. *Aquaculture production statistics 1987–1996.* FAO Fisheries Circular No. 815, Rev. 10. FAO, Rome. 197 pp.

Froese, R. & Pauly, D., eds. 1998. *FishBase 98: concepts, design and data sources.* With two CD-ROMs. ICLARM, Manila.

Kirkegaard, E. 1997. *Stock enhancement and sea ranching as an alternative to traditional management.* Paper presented at the First International Symposium on Stock Enhancement and Sea Ranching, Bergen Norway, 8–11 September 1997.

MacCall, A.D. 1989. Against marine fish hatcheries: ironies of fishery politics in the technological era. *Cal. COFI Reports*, 30: 46–48.

Masuda, R. & Tsukamoto, K. 1998.Stock enhancement in Japan: review and perspective. *Bull. Mar. Sci.*, 62: 337–358.

McCarty, C.E., McEachron, L.W. & Rutledge,W.P. 1993. *Beneficial uses of marine fish hatcheries: the Texas experience.* The International Symposium on Sea Ranching of Cod and Other Marine Species, Arendal, Norway, 15–18 June 1993. Programme and Abstracts. 54 pp.

Moksness, E. & Stoele, R. 1997. Larviculture of marine fish for sea ranching purposes: is it profitable? *Aquaculture*, 155(1–4): 345–357.

Appendix 1

Species	Country Hatchery Production	Env.	Reported period (years)	Reported years	Countries ASFA	Countries other sources
Acanthopagrus latus	United Arab Emirates	m	1	1997		
Acanthopagrus schlegeli	Republic of Korea	m	9	1986–1995	Japan	
Acipenser brevirostrum	USA	mbf	9	1989–1997		
Acipenser fulvescens	USA	mbf	3			
Acipenser guldenstadti	Ukraine	mbf	7	1984–1988, 1992, 1993		
Acipenser oxyrhynchus	USA	mbf	5	1994–1997		
Acipenser spp.	Iran	mbf	2	<1990		
Acipenser spp.	USA	mbf	4	1987, 1988, 1995, 1997		
Acipenser sturio	France	mbf	1	1992		
Acipenseridae	Azerbaijan	mbf	3	1989–1991		
Acipenseridae	Georgia	mbf	2	<1990		
Acipenseridae	Russian Federation	mbf	6	1992–1997		
Acipenseridae	Ukraine	mbf	4	<1991		
Acipenseridae	USSR	mbf	6	1986–1991		
Alosa sapidissima	No data	mbf			USA (Pennsylvania)	
Anadara broughtonii	No data	mbf				Japan
Anguilla anguilla	Denmark	mbf	1		Denmark	
Anguilla anguilla	France	mbf	1			
Anguilla anguilla	Germany	mbf	4			
Anguilla anguilla	Italy	mbf	5			
Anguilla anguilla	Lithuania	mbf	1			
Anguilla japonica	Japan	mbf	3			
Atractoscion nobilis	No data	m			USA (California)	
Centropomus undecimalis	No data	mbf			USA (Florida)	
Chelonia mydas	No data	mbf				Philippines
Chrysophrys major	Republic of Korea	m	2	1986,1987		
Coregonus lavaretus	Estonia	mbf	6	1992–1997		
Coregonus lavaretus	Finland	mbf	2	<1987		
Coregonus lavaretus	Kyrghyzstan	mbf	1	1995		
Coregonus lavaretus	Lithuania	mbf	3	1992, 1996, 1997		
Coregonus lavaretus (autumn fry)	Poland	mbf	1	1993, 1996, 1997		
Coregonus lavaretus (larvae)	Poland	mbf	3	1992		
Coregonus lavaretus (summer fry)	Poland	mbf	1	1992		
Coregonus spp.	Finland	mbf	10	1984–1987		
Coregonus spp.	France	mbf	3	<1987		
Coregonus spp.	Russian Federation	mbf	6	1992–1997		
Coryphaena hippurus	No data	mb			Hawaii	
Crassostrea gigas	Japan	mb	3	1994, 1996		
Crassostrea rhizophorae	Grenada	mb	1	1984		
Crassostrea spp.	Mexico	m	1	1985		
Crassostrea virginica	Grenada	mb	1	1984	USA	
Dicentrarchus labrax	Germany	mb	1	1997		

Note. m, b and f refer to marine, brackish and freshwater environments respectively.

Species	Country Hatchery Production	Env.	Reported period (years)	Reported years	Countries ASFA	Countries other sources
Dicentrarchus labrax	Cyprus	mbf	1	1991		
Dicentrarchus labrax	Egypt	mbf	3	1995–1997		
Dicentrarchus labrax	Tunisia	mbf	1	1990		
Epinephelus fuscoguttatus	Singapore	m	1	1991		
Fugu rubripes	Republic of Korea	mb	1	1986		
Gadus macrocephalus	No data	m			USA (Puget Sound)	
Gadus morhua	Norway	m	2	1986, 1987	Norway, Denmark, Canada	
Gambusia gaigei	USA	mb	3	1989, 1992, 1993		
Haliotis discus hannai	No data	mbf				Japan
Haliotis diversicolor aguatilis	Taiwan Province of China	m	2	1996, 1997		
Haliotis fulgens	Mexico	m	1	1985		
Haltotis notohaliotis discus	Republic of Korea	m	3	1987, 1991, 1992		
Hemicentrotus pulcherrimus	Republic of Korea	m	1	1992		
Homarus americanus	No data	mbf				USA
Homarus gammarus	UK (Scotland)	m	1	1997		
Homarus gammarus	No data	m			Norway, UK, USA (Maine)	
Huso huso	Ukraine	mbf	2	<1987		
Hybrid Morone chrysops, Morone saxatilis	USA	mbf	8	1985, 1989–1994, 1996		
Lampetra fluviatilis	Estonia	mbf	1	1992		
Lampetra fluviatilis	Latvia	mbf	6	1991, 1993–1997		
Lateolabrax japonicus, Lates calcarifer	Taiwan Province of China	mbf	1	1997		
Lates calcarifer	Australia	mbf	6	1985, 1987–1991		
Lates calcarifer	Brunei	mbf	1	1993		
Lates calcarifer	French Polynesia	mbf	1	1991		
Lates calcarifer	Malaysia	mbf	1	1995		
Lates calcarifer	Singapore	mbf	6	1986–1991		
Lepidochelys kempi	No data	mbf				USA
Mercenaria mercenaria	No data	mb			USA (North Carolina, New York)	
Mithrax spinosissimus	Dominican Republic	m	1	1984		
Mithrax spinosissimus	Turks & Caicos Islands	m	1	1992		
Morone saxatilis	USA	mbf	14	1984–1997	USA	
Morone spp.	Egypt	mbf	1	1996		
Mugil auratus	Ukraine	mbf	4	<1987		
Mugil capito	Israel	mbf	1	1994		
Mugil cephalus	Israel	mbf	2	1985, 1996	Hawaii	
Mugil cephalus	Republic of Korea	mbf	1	1993		
Mugil cephalus, Liza ramada	Egypt	mbf	6	1991–1997		
Mugil incilis	Colombia	mb	3	1985–1987		
Mugil spp.	Colombia	mbf	2	<1989		

Species	Country Hatchery Production	Env.	Reported period (years)	Reported years	Countries ASFA	Countries other sources
Mugil spp.	Ukraine	mbf	6	1988–1993		
Oncorhynchus clarki	USA	mbf	12	1984, 1986	USA (California)	
Oncorhynchus gorbuscha	Chile	mbf	2	<1986	Russian Federation, USA (Alaska)	
Oncorhynchus gorbuscha	USA	mbf	12	1992, 1993		
Oncorhynchus keta	Chile	mbf	2	<1987	USA (Oregon), Japan	
Oncorhynchus keta	Republic of Korea	mbf	12	1996, 1997		
Oncorhynchus keta	USA	mbf	14	1984–1997		
Oncorhynchus kisutch	Chile	mbf	2	<1988	USA, Canada	
Oncorhynchus kisutch	Cyprus	mbf	1	1989		
Oncorhynchus kisutch	France	mbf	1	1987		
Oncorhynchus kisutch	USA	mbf	14	1984–1997		
Oncorhynchus masou	Chile	mbf	3	<1987		
Oncorhynchus masou	Republic of Korea	mbf	4	<1990		
Oncorhynchus mykiss	Argentina	mbf	7	1984, 1986, 1987, 1989, 1990, 1993, 1996		
Oncorhynchus mykiss	Australia	mbf	7	<1987		
Oncorhynchus mykiss	Belgium	mbf	11	1984, 1985, 1990		
Oncorhynchus mykiss	Brazil	mbf	2	<1987		
Oncorhynchus mykiss	Chile	mbf	4	<1988		
Oncorhynchus mykiss	Colombia	mbf	8	1984–1991		
Oncorhynchus mykiss	Cyprus	mbf	13	1996		
Oncorhynchus mykiss	Denmark	mbf	1	1986		
Oncorhynchus mykiss	Estonia	mbf	2	1992, 1996		
Oncorhynchus mykiss	Finland	mbf	12	1984, 1985		
Oncorhynchus mykiss	France	mbf	6	1992–1997		
Oncorhynchus mykiss	Iran	mbf	6	1989–1993, 1995		
Oncorhynchus mykiss	Republic of Korea	mbf	3	<1986		
Oncorhynchus mykiss	Latvia	mbf	9	1984–1992		
Oncorhynchus mykiss	Madagascar	mbf	1	1986		
Oncorhynchus mykiss	Mexico	mbf	3	1985, 1996, 1997		
Oncorhynchus mykiss	Morocco	mbf	12	1986, 1987		
Oncorhynchus mykiss	Norway	mbf	2	<1987		
Oncorhynchus mykiss	Norway	mbf	3	1988–1990		
Oncorhynchus mykiss	Peru	mbf	5	1986, 1994–1997		
Oncorhynchus mykiss	Romania	mbf	1	1997		
Oncorhynchus mykiss	UK (Northern Ireland)	mbf	7	1990–1992, 1994–1997		
Oncorhynchus mykiss	USA	mbf	14	1984–1997		
Oncorhynchus mykiss	Uzbekistan	mbf	2	1993, 1994		
Oncorhynchus mykiss	Venezuela	mbf	1	1993		
Oncorhynchus mykiss (fry 1+)	Poland	mbf	1	1992		
Oncorhynchus mykiss, *Oncorhynchus masou*, *Oncorhynchus rhodorus*, *Oncorhynchus kisutch*, *Salvelinus pluvius*	Japan	mbf	3	1994–1996		

Species	Country Hatchery Production	Env.	Reported period (years)	Reported years	Countries ASFA	Countries other sources
Oncorhynchus nerka	USA	mbf	14	1984–1997	USA (Alaska)	
Oncorhynchus spp.	USA	mbf	2	<1986		
Oncorhynchus tshawytscha	Australia	mbf	5	1986, 1988–1991	USA, Canada	
Oncorhynchus tshawytscha	Chile	mbf	2	<1988		
Oncorhynchus tshawytscha	New Zealand	mbf	2	<1988		
Oncorhynchus tshawytscha	USA	mbf	14	1984–1997		
Ophiodon elongatus	No data	m			USA	USA
Oplegnathus fasciatus	Republic of Korea	m	6	1987, 1991–1995		
Ostrea edulis	UK (Scotland)	m	1	1997		
Pagrus major	Japan	m	1		Japan	
Pagrus major	Republic of Korea	m	9	1986, 1988–1995		
Pagrus major	China (Taiwan)	m	1	1997		
Pagrus major, Acanthopgrus schlegeli, Ebynnis japonica	Japan	m	2	1994–1996		
Panope abrupta	No data	mbf				USA
Paralichthys californicus	No data	mb			USA (California)	
Paralichthys olivaceus	Japan	m	2	1995, 1996	Japan, China (1987)	
Paralichthys olivaceus	Republic of Korea	m	9	1987–1995		
Patinopecten yessoensis	Japan	m	3	1994–1996	Japan, France	
Pecten maximus	UK (Scotland)	m	1	1997		
Pecten novaezelandiae	No data	mbf				New Zealand
Penaeus (orientalis) chinensis	China	mb	1	1985		
Penaeus japonicus	Japan	mb	3	1994–1996	Japan	
Penaeus japonicus	Republic of Korea	mb	7	1986–1992		
Penaeus japonicus	Taiwan Province of China	mb	2	1994, 1997		
Penaeus merguiensis	Malaysia	mb	1			
Penaeus merguiensis	Singapore	mb	4	1986–1989	Singapore	
Penaeus monodon	Brunei	mb	2	1994, 1995		
Penaeus monodon	Republic of Korea	mb	2	1994, 1995		
Penaeus monodon	Mauritius	mb	1	1997		
Penaeus monodon	Seychelles	mb	1	1989		
Penaeus orentalis kishimouye	Republic of Korea	mb	8	1987–1992, 1994, 1995		
Penaeus spp.	Egypt	mb	1	1995		
Penaeus stylirostris	Panama	mb	1	1992		
Penaeus vannamei, Penaeus stylirostris	Panama	m	1	1991		
Peneaus monodon	Australia	mb	1	1990		
Perna perna	Mozambique	mb	1	1986		
Pincta fucata martensii	Republic of Korea	m	1	1992		
Pinctada fucata	Japan	mb	3	1994–1996	India	
Platichthus flesus luscus	Ukraine	mbf	3	1991–1993		
Platichthys flesus	No data	mbf			Denmark, Netherlands (1977)	
Plecoglossus	Republic of Korea	mbf	1	1993		
Plectroplites ambiguus	Australia	mbf	1	1985		

Species	Country Hatchery Production	Env.	Reported period (years)	Reported years	Countries ASFA	Countries other sources
Pleuronectes platessa	No data	mb			Denmark, Netherlands (1977)	
Polydactylus sexfilis	No data	mbf				Hawaii
Porphyra spp.	Japan	mb	2	1994, 1998		
Portunus trituberculatus	Republic of Korea	m	7	1988–1992, 1994, 1995		
Portunus trituberculatus	No data	mbf				Japan
Pseudocaranx dentex	No data	mb			Japan	
Pseudocaranx dentex	No data	mbf				Japan
Puntazo puntazo	Cyprus	m	1	1991		
Salmo salar	Argentina	mbf	5	1984, 1986, 1987, 1989, 1990		
Salmo salar	Australia	mbf	2	<1987		
Salmo salar	Denmark	mbf	1	1986		
Salmo salar	Estonia	mbf	4	1992, 1994, 1996, 1997		
Salmo salar	Faeroe Islands	mbf	2	<1989		
Salmo salar	Finland	mbf	12	1984, 1985		
Salmo salar	France	mbf	8	1985, 1986, 1992–1997		
Salmo salar	Iceland	mbf	8	1989, 1991–1997		
Salmo salar	Latvia	mbf	14	1984–1997		
Salmo salar	Lithuania	mbf	1	1993		
Salmo salar	Norway	mbf	5	1986–1990		
Salmo salar	Poland	mbf	2	1995, 1996		
Salmo salar	Sweden	mbf	12	1984, 1985		
Salmo salar	UK (England/ Wales)	mbf	4	1992–1995		
Salmo salar	UK (Northern Ireland)	mbf	8	1989–1992, 1994–1997		
Salmo salar	UK (Scotland)	mbf	1	1986		
Salmo salar	USA	mbf	14	1984–1997		
Salmo trutta	Australia	mbf	1	1997	Norway, Finland, Canada	
Salmo trutta	Denmark	mbf	1	1986		
Salmo trutta	Faeroe Islands	mbf	2	<1987		
Salmo trutta	Finland	mbf	12	1984, 1985		
Salmo trutta	France	mbf	9	1985–1987, 1992–1997		
Salmo trutta	Iceland	mbf	2	1988, 1989		
Salmo trutta	Latvia	mbf	6	1991, 1993–1997		
Salmo trutta	Lithuania	mbf	3	1992–1994		
Salmo trutta	Morocco	mbf	13	1986		
Salmo trutta	Norway	mbf	4	<1990		
Salmo trutta	South Africa	mbf	3	1993–1995		
Salmo trutta	Sweden	mbf	12	1984, 1985		
Salmo trutta	UK (England/ Wales)	mbf	4	1992–1995		
Salmo trutta	UK (Northern Ireland)	mbf	5	1992, 1994–1997		
Salmo trutta	USA	mbf	12	1984, 1986		
Salmo trutta labrax	Georgia	mbf	8	1984–1991		
Salmo trutta trutta	Estonia	mbf	6	1992–1997		

Species	Country Hatchery Production	Env.	Reported period (years)	Reported years	Countries ASFA	Countries other sources
Salmo trutta trutta	Poland	mbf	3	1992, 1995, 1996		
Salvelinus alpinus	Finland	mbf	2	<1987		
Salvelinus alpinus	France	mbf	8	1985, 1986, 1992–1997		
Salvelinus alpinus	Iceland	mbf	2	1988, 1989		
Salvelinus alpinus	Switzerland	mbf	2	1996, 1997		
Salvelinus alpinus	USA	mbf	5	1986–1990, 1991		
Salvelinus confluentus	USA	mbf	1	1996		
Salvelinus fontinalis, Salvelinus alpinus, Thymallus thymallus	Norway	mbf	2	<1987		
Salvelinus malma	USA	mbf	1	1984		
Salvelinus spp.	Finland	mbf	10	1984–1987		
Salvelinus spp.	Norway	mbf	3	1988–1990		
Scallop	Russian Federation	mb	3	1986–1988		
Sciaenops ocellatus	USA	mb	3	1984, 1988	USA (Texas)	
Scophthalmus maximus	No data	mbf				Denmark
Scylla serrata	Australia	mb	4	1986–1989		
Sebastes schlegeli	Republic of Korea	m	7	1988–1992, 1994, 1995	Japan	
Seriola quinqueradiata, S. aureovitlata, S. dumerili	Japan	m	3	1994–1996		
Siganus canaliculatus	United Arab Emirates	mb	2	1989, 1991		
Sparus aurata	No data	mb			Tunisia (lagoons)	
Sparus auratus	Cyprus	mb	1	1991		
Sparus auratus	Egypt	mb	3	1995–1997		
Sparus auratus, Dicentrarchus labrax	Cyprus	mb	1	1992		
Strombus gigas	Belize	m	1	1986		
Strombus gigas	Sao Tome	m	1	1984		
Strombus gigas	Turks & Caicos Islands	m	2	1992, 1993		
Strongylocentrotus lividus	Republic of Korea	m	1	1992		
Sulculus diversicolor aquatilis	Republic of Korea	m	2	1991, 1992		
Takifugu rubripes	No data	mbf				Japan
Tridacna derasa	Micronesia	m	1	1986	Solomon Islands, Philippines	
Tridacna derasa	Tonga	m	1	1997		
Tridacna maxima	Tonga	m	2	1996, 1997		
Tridacna spp.	Fiji	m	1	1992		Solomon Islands, Indo-Pacific, Philippines
Trochus niloticus	New Caledonia	m	1	1989		Australia, Indonesia, Vanuatu
Trochus niloticus	Tonga	m	2	1996, 1997		
Turbo marmoratus	Tonga	m	1	1997		
Undaria	Japan	m	3	1994, 1995		

An integrated development programme for marine stocking: the Norwegian example

Terje Svåsand
Ann-Lisbeth Agnalt
Ove T. Skilbrei
Institute of Marine Research
P.O. Box 1870 Nordnes, 5817 Bergen, Norway

Jørgen Borthen
Directorate of Fisheries, 5002 Bergen, Norway

Tor Heggberget
Norwegian Institute for Nature Research, 7005 Trondheim, Norway

ABSTRACT

In Norway a national sea-ranching programme was launched in 1990 financing release projects with the four species; European lobster (*Homarus gammarus*), Atlantic cod (*Gadus morhua*), Atlantic salmon (*Salmo salar*) and Arctic char (*Salvelinus alpinus*). The program aimed to elucidate biological, ecological, juridical and economic requirements for a new coastal industry. For one species, the lobster, the releases were done intending mainly to increase or enhance a local stock in a long-term perspective, while in the other three species the releases were made to evaluate the possibility to obtain a direct catch profit after a period spent in the ocean.

Knowledge acquired through the Norwegian sea-ranching programme PUSH has provided valuable insight into factors that regulate fish production in our fjord and coastal areas. It was not possible to develop commercial sea-ranching activities for any of the species concerned. However, biological and ecological requirements have been clarified. One of the prerequisites of stock enhancement and sea ranching is to be able to produce sufficient number of viable juveniles. This was accomplished for all species involved, and for some a further refinement to ensure higher survival and growth rate was suggested.

A total of 128 000 lobster juveniles were released from 1990 to 1994 and by the end of 1999 recapture percentage ranged from 2.2 to 9.2, although the recapture phase has not yet ended. Differences between wild and cultured lobsters have been found in claw morphology and abdominal width. However, the significance of such has not been possible to measure or even evaluate. It was shown that cultured lobster do not replace wild lobster, but represents an addition to the stock. It was also found that with the ruling minimum legal size MLS of 25 cm total length all females have spawned once before captured and a majority also twice. Furthermore, berried females of cultured origin have since 1995 made a significant proportion of the total number of berried females caught. Hence, the total stock has been strengthened but with the lack of appropriate management legislations it is uncertain of the long-term impact.

In various coastal and fjord locations 720 000 tagged cod juveniles were released providing valuable information on migration, survival and growth. Recapture

percentages ranged from zero to 30 percent depending on area, time and size at release. In most of the release areas, a positive correlation between the size at release and survival was found. Individual growth was highest in the outer coast areas. Ecosystem analyses were performed for the most important release areas and large differences were found in carrying capacity, growth and survival rates.

A total of 1.2 million Atlantic salmon smolts were released at four release sites. No systematic differences in recapture rate or straying could be found between releases made in watercourses at the coast and those in the fjord systems, but the geographical straying pattern differed between the specific release sites. In general, mean recaptures of year–classes of smolts were low, ranging from 0.5 to 3.8 percent. However, there was a high degree of variation between release groups; from close to zero to 12.8 percent total tag recovery. These differences, which seemed to be related to the treatment and origin of the released fish, probably indicates a potential for further optimisation of the methods of salmon sea ranching.

About 123 000 individuals of Arctic char were released, and in comparison with other salmonid species the recapture percentages were high, but somewhat variable. Ocean survival was strongly correlated with size or age of the fish. The bottleneck in sea ranching of Artic char is the high mortality in the first-time seaward migrants.

In general, survival rates in the sea were too low to make sea-ranching activity profitable, and the market price for Atlantic cod, Atlantic salmon and Arctic char would have to double or triple to make commercialisation worthwhile. However, reducing costs per animal released as well as including steps to improve survival and growth are possible approaches that can improve the prospects of profitability. Not even with the lobster does it look as though there be any development of private enterprises in the short run, although enhancement seems to have the potential to become socio-economically viable. In this respect, offspring or second-generation organisms must be taken into consideration and it is assumed that the effective or total production will increase as a result of the releases.

Despite the fact that evaluations of the economics of commercial sea ranching of Atlantic cod, Atlantic salmon, Arctic char and European lobster are discouraging, we should keep in mind that the work of the PUSH programme constituted the first attempts to evaluate large-scale releases of tagged individuals. This research activity might be characterised as trial and error experiments, and seven years is a short period in which to fully determine which ecological and physiological factors are decisive for growth and survival. To focus on recapture rates is short-sighted and ignores the fact that adequate knowledge of optimal times and places of release, not to mention the quality of the animals required to ensure high survival, was not available at the beginning of the 1990s. As Leber (1999) emphasises, stock-enhancement research shows many of the characteristics of a new science, and the data presented in this paper should be regarded as such.

BACKGROUND

The oceans of the world offer a huge potential for increasing food production. During the past 150 years several projects have attempted to increase the yield from a fishery by releasing juveniles. The idea of stocking goes back to the 17th century, with the introduction of such techniques as transplanting fish and constructing artificial reefs in Japan and China. The first research activities on marine sea-ranching in Norway dates back to the end of the last century, when G.O. Sars discovered and described the early life stages of Atlantic cod (*Gadus morhua*) in 1864 (Sars 1879). In 1883 a marine hatchery was built in Flødevigen in southeastern Norway, marking the beginning of a boom in hatcheries that lasted for almost 100 years, with hatcheries also being built in the United States, Canada, the United Kingdom of Great Britain and other countries (Kirk, 1987). However, there was little or no evidence that these early stocking activities offered any benefits, and interest in these methods gradually faded. Recent experiments using marked larvae and juveniles have brought us information and knowledge that may explain the failure of these early stocking experiments (Kristiansen *et al.*, 1997). Until quite recently, a bottleneck in the use of larvae and small juveniles in stocking studies has been the lack of suitable tagging techniques.

Interest in sea ranching was aroused again in the 1980s, along with the development of suitable marks and tagging methods. In Norway tagging and release programmes were launched using smolts of Atlantic salmon (*Salmo salar*) and Atlantic cod juveniles, and some release experiments were also carried out using juveniles of the European lobster (*Homarus gammarus*), though these were released without physical tags. Promising initial results formed the basis for a larger national sea-ranching programme, which is described below.

The Norwegian sea-ranching programme (PUSH)

In spring 1989 the Norwegian Ministry of Fisheries and Ministry of the Environment decided to appoint a committee of scientists to assess, from a biological point of view, the potential for sea ranching anadromous fish species in Norway. The committee recommended that all on-going as well as commencing projects should be coordinated by a national sea-ranching programme. On September 6, 1990 this became a reality when the Norwegian Government resolved, with the approval of Parliament, to launch a Norwegian Sea Ranching Programme (PUSH) (Anon., 1989; Anon., 1990). This would involve not only anadromous species such as Atlantic salmon and Arctic char (*Salvelinus alpinus*), but also Atlantic cod and European lobster. A board was appointed with representatives from industry, research institutions and management, while steering committees were set up for each of the four species, with representatives from all parties involved, and with funding from PUSH. The steering committees met several times a year to discuss results, progress and problems. It was regarded as fruitful for the progress of the projects that various parties participated in the meetings so that questions and problems could immediately be clarified. The steering committees have also been in charge of the final species reports (Anon., 1998a; Borthen *et al.*, 1998; Skilbrei *et al.*, 1998; Svåsand *et al.*, 1998a). The proposed timeframes varied from five to seven years, but in practice the individual projects lasted for seven years, except for char.

In total the Norwegian sea-ranching programme (PUSH) funded 40 individual projects between 1990 and 1997. The annual budget varied from 7 to 39 million NKr, with a total of 178 million NKr (lobster 19 million; cod 63 million; salmon 58 million; char 20 million; analysis of economics and management, and miscellaneous projects 8 million; administration 10 million) (Anon., 1998b).

AIMS

The programme aimed to elucidate the biological, ecological, juridical and economic requirements of a new coastal industry based on sea-ranching European lobster, Atlantic cod, Atlantic salmon and Arctic char. The long-term goal was to develop release and harvesting methods that would be economically viable and ecologically justifiable.

Sea ranching is defined as the "economical exploitation of a potential product in the sea by releasing cultured organisms that are to be harvested and sold". However, wild juveniles have also been used in some of the release experiments. A distinction should be made between releases that are intended to increase or enhance stocks in a longer-term perspective in order to increase the potential future yield (stock enhancement), and releases made to obtain a direct catch profit after a period spent in the ocean (sea ranching). Both strategies have formed part of the programme that also aimed to stimulate the cultivation of char and cod in particular.

BIOLOGICAL AND POLITICAL CONSIDERATIONS

The last 25 to 30 years of development in intensive coastal aquaculture have indicated certain limitations of the marine environment. More extensive forms of aquaculture might therefore assume greater importance in the future. Parliamentary White Paper (St. prp.) No.95 (1989–1990) says Anon., 1989 translated from Norwegian):

> *"Sea ranching will be based on nature's own carrying capacity, where the harvesting of resources is adapted to the ecosystem."……"One might also be optimistic regarding the prospects of developing aquaculture as a means of strengthening traditional fisheries through stock enhancement, at least within local stocks."……"Released fish will contribute to local stocks in the fjords and near coastal areas".*

There was a strong incentive to stimulate the development of business activities in coastal rural areas, in order to improve the economic situation in these areas. In 1988 Norway adopted a ban on using driftnets for catching salmon, though with strong objections from fishermen, and there was a need to make amends for this ban. Sea ranching of salmon in Norway, has been carried out in rivers since the last Second World War, but it was not until after the 1950s that it became systematic, with the adoption of a scientific approach. Tagging of hatchery-reared smolts showed that adults returned with high precision to their point of release in rivers or estuaries. Releases of salmon smolts directly into the sea increased recaptures of adults but also increased straying because mature fish had no "native" river to return to. The main strategy adopted for future salmonid ranching in Norway was therefore to release smolts in relation to freshwater, i.e. in rivers or in estuaries close to river mouths.

Lobster, cod and salmon stocks had all been descending during the ten years before PUSH started. In the late 1980s there was a severe reduction in Atlantic cod stocks in Norwegian waters, and lobster stocks were also at a critical level. It was believed that it would be possible to re-establish production back to "normal" levels. Prices were high in the late 1980s, and viable economic activity was assumed to be achievable. Highest prices were obtained for lobster, for which fishermen were paid from 150 to 240 NKr per kilogram, i.e. about US$20 to US$30. In the period before 1990 several stocking experiments were carried out, with promising results for all four species. With regard to char, a common species in northern Norway, there was a desire to involve this part of the country as well. These factors formed an important background for the proposed PUSH programme, as it was presented in 1989. The following sections present a survey of the results concerning the individual species involved in the PUSH programme.

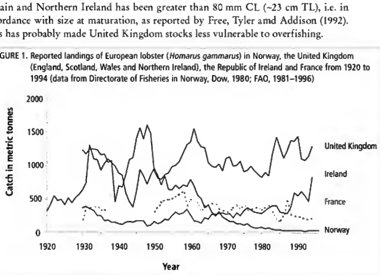
European lobster *(Homarus gammarus)*

REVIEW OF FISHERY

Stocks of European lobster have supported valuable local fisheries in Norway since around 1600 (Boeck, 1869; Dannevig, 1936). Available statistics show that between 1815 and 1930 annual landings fluctuated around an average of about 900 000 individuals (about 500 tonnes). At that time there were no restrictions in the fishery, which became an issue to be questioned for hundreds of years. In 1932 landings rose sharply to a peak of 1 300 tonnes or about 2.8 million individuals (Figure 1), partly as a result of good recruitment in south-western Norway (Dannevig, 1936) and partly because of an increase in fishing effort off the Norwegian Skagerrak coast (Tveite, 1991). After the Second World War landings fell slowly until the early 1960s. However, since the 1960s there has been a severe reduction in the annual harvest, which currently lies at about 30 tonnes. The Norwegian share of European lobster landings varied from 20 to 50 percent before 1960, whereas it was only about 1 percent in 1996. No other country in Europe has experienced such a dramatic decrease in its lobster harvest.

Stock management legislation in Norway has been based on close seasons and minimum legal sizes (MLS). A close season was introduced in 1849, and is currently set from 1 June to 30 September. In 1879 the MLS was set to 21 cm total length (~71 mm carapace length (CL)) and 85 years later, in 1964, was increased by 1 cm (~75 mm CL). The unwise management strategy of fishing females before maturation was pointed out by fisheries scientists many years ago (Boeck, 1869; Appelöf, 1909), but the suggestions of an MLS of 25 cm TL (~88 mm CL) in western Norway and 24 cm TL in southern Norway were not enforced until 1993. By contrast, from 1951 until 1966 the United Kingdom banned landings of berried females (Bennet and Edwards 1981), and for almost 40 years the MLS in the United Kingdom of Great Britain and Northern Ireland has been greater than 80 mm CL (~23 cm TL), i.e. in accordance with size at maturation, as reported by Free, Tyler amd Addison (1992). This has probably made United Kingdom stocks less vulnerable to overfishing.

FIGURE 1. Reported landings of European lobster (*Homarus gammarus*) in Norway, the United Kingdom (England, Scotland, Wales and Northern Ireland), the Republic of Ireland and France from 1920 to 1994 (data from Directorate of Fisheries in Norway, Dow, 1980; FAO, 1981–1996)



REVIEW OF PREVIOUS CULTIVATION PROJECTS

In the mid-1880s G.M. Dannevig hatched larvae of the European lobster at Flødevigen in southern Norway, and he was the first to obtain survival until settlement (Appelöf, 1909). More or less at the same time, larvae from the closely related American lobster (H. americanus) were being hatched in Woods Hole, United States (Aiken and Waddy, 1995). Interest in stocking fishing grounds with hatchery-reared larvae/juveniles grew when lobster landings in Canada and Newfoundland declined dramatically during the 1880s (Waddy and Aiken, 1998). There was general concern in Norway when lobster landings also declined on this side of the Atlantic in the same period, the 1880s. In the early 1900s a large number of hatcheries were established in the North American continent as well as in Europe (Aiken and Waddy, 1995). On the eastern coast of the United States alone some 880 million newly hatched larvae were released between 1885 and 1903. In western Norway a large holding facility was built at Kvitsøy, one of the major lobster fishing areas. The purpose was to maintain berried females until hatching, and with this effort increase the total recruitment in the area (Appelöf, 1909). Large numbers of newly hatched larvae were subsequently identified, but older ones were never found. Although a few young lobsters were found in the holding facility four or five years later, and most likely having grown up there, the conclusion was that this gave few measurable results. Further effort was therefore dedicated to improve hatching techniques, but it was not until in 1923 that a method of mass-producing newly settled larvae was developed. In the same year, a lobster hatchery was built in Flødevigen in southern Norway, but as previously noted, in France and the United Kingdom of Great Britain and Northern Ireland several hatcheries had already been set up. However, common features of all of these stocking projects around the world was the lack of methods for identifying the cultured and released animals and thus proves that they could survive until recruitment to the fishery.

Further progress in this matter was not made until the mid-1970s. In Canada, several private companies aimed to commercialise lobster production, but unfortunately none were reported as successful (Waddy and Aiken, 1998). In Norway, S. Grimsen and J.G. Balchen, on behalf of SINTEF (Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology) and the tobacco company Tiedemanns, successfully raised approximately one-year-old lobster juveniles for release purposes. This resulted in the establishment of a lobster hatchery at Kyrkesæterøra in mid-Norway. Tveite and Grimsen (1995) reported that from 1979 to 1987, 62 500 lobster juveniles were released on the Norwegian coast, from Bulandet in the mid-west to Kragerø in the southeast of the country. As a result of the cultivation process a majority of these animals developed two scissors claws instead of the normal set of one scissors and one crusher claw. These were commonly called "Tiedemanns lobsters", and after five to eight years could be recognised in the commercial fishery. In some areas, fishermen reported a substantial increase in their catches due to "Tiedemanns lobsters" (Tveite and Grimsen, 1995).

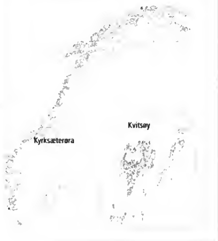
In the mid-1980s tagging using magnetically binary-coded tags was also found to be suitable for juvenile lobsters (Jefferts *et al.*, 1963; Wickins *et al.*, 1986). This development finally made it possible to evaluate lobster release programmes quantitatively, and triggered a number of release experiments in France (Latrouite and Lorec 1991, Latrouite 1998), Wales (Cook, 1995; Bannister and Addison, 1998), England (Bannister *et al.*, 1994; Bannister and Addison, 1998), Scotland (Burton *et al.*, 1994), Ireland

(Browne and Mercer, 1998) and Norway (reported here). In 1989, the Institute of Marine Research in Bergen (Norway) took over the Kyrkesæterøra Lobster Hatchery in mid–Norway, and in the following year the European lobster was included as one of the four species in the Norwegian Sea Ranching Programme (PUSH).

METHODOLOGY OF THE STOCK-ENHANCEMENT PROJECT

The choice of the large-scale release area fell on Kvitsøy, a group of islands near the opening of Boknafjord in southwestern Norway (Figure 2). This choice was based on a number of factors. The islands are separated from surrounding areas by deep-sea trenches, and out-of-area migration was expected to be a minor problem. Kvitsøy is also known for its historically high catches of lobster and must once have sustained a large population, as well have been very productive with respect to settlement of naturally produced larvae. However, the present situation is very different. Landings are extremely low compared to earlier times, and there are indications of a long-lasting failure in recruitment. Selections of broodstock, larval rearing, release strategy etc. are outlined below. For more detailed information see Uglem and Grimsen (1995), Uglem *et al.* (1995), Borthen *et al.* (1998) and Agnalt *et al.* (1999).

FIGURE 2. The lobster hatchery at Kyrksæterøra, Norway, and the release site at the Islands of Kvitsøy



BROODSTOCK SELECTION

Wild berried females were captured at Kvitsøy by local fishermen and sent to the hatchery at Kyrksæterøra (Figure 2). In some seasons there were difficulties in obtaining sufficient numbers of ovigerious females, and in the early phase of the project supplies were made from elsewhere in regions around Kvitsøy, and berried females were even introduced from Scotland. Offspring from the Scottish broodstock were not intended to be released at Kvitsøy, although this may have happened unintentionally in the first release year, though at any rate only in small numbers (S. Grimsen and I. Uglem personal communication, 2000). Since 1991, only berried females from Kvitsøy have been used as broodstock. After hatching, the broodstock females were released back to the islands of Kvitsøy.

LARVAL REARING

A detailed description of the processes that took place in the hatchery and nursery is provided by Grimsen *et al.* (1987), Uglem and Grimsen (1995) and Uglem *et al.* (1995), but these followed Wickins *et al.* (1986). The hatchery was supplied with water heated through a heat-exchange process with thermal effluent from the local ferro-silicon smelter, Hølla Smelteverk. On arrival, the berried females were placed in individual compartments. Hatched larvae were collected in a net-screened box before transferred to large rearing tanks (250–350 litres) with continuous water flow. The larvae were mainly fed frozen adult brine shrimp (*Artemia* spp.). When the larvae reached development stage IV, the last pelagic stage before settling, they were transferred to trays with separate divisions. Each tray, containing 120 individuals, was put into a circular pool with a diameter of 50 m. The pool was divided into 11 concentric rings, and the trays circulated within each ring. From 1990, shell sand was added in the settling phase to induce the development of a crusher claw (Wickins *et al.*, 1986; Korsøen, 1994). The large-scale hatchery aimed to produce annually from 50 000 to 70 000 nine-month old juveniles. However, although a high survival rate was obtained in the small-scale research facilities, survival in the large-scale hatchery remained low, at only three to five percent. Nevertheless, sufficient numbers of juveniles were produced to carry out large-scale releases at Kvitsøy (see Table 1).

TABLE 1. Total number of cultured lobster juveniles released at Kvitsøy from 1990 to 1994 (number released without a tag is indicated in parentheses), and number recaptured from autumn 1992 to autumn 1999 (updated and modified from Agnalt *et al.*, 1999). Number recaptured is separated into above minimum legal size (MLS; commercial landings) and below MLS (selected samples)

Release Year	Hatching year	Number tagged	No. recaptured above MLS	No. recaptured below MLS	Total recapture %
1990	1988	14 977 (1 400)	523	21	3.6
1990	1989	8 726 (957)	774	48	9.4
1991	1990	29 693	1 607	103	5.8
1992	1991	29 919	1 894	205	7.0
1993	1992	11 784	523	64	5.0
1994	1993/94	32 846	668	108	2.4
		127 945 (2 357)	5 989	549	5.1

TAGGING METHOD AND RELEASE STRATEGY

Before transportation to the release area, a magnetically coded microwire tag (North West Marine Technology Inc.) was injected into the base of the 5th pereiopod. The tags were 1 × 0.5 mm or 0.5 × 0.5 mm in size, and could only code for batches or groups of lobster. Uglem and Grimsen (1995) reported a tagging mortality from one to four percent, and a tag loss of about 10 percent after three months, which is in accordance with previously reported figures (Wickins *et al.*, 1986; Latrouite and Lorec, 1991; Burton 1992). The lobster juveniles were released by fishermen at sea surface along the shore at depths no greater than 10 m. This release strategy is rather crude in comparison with releases made by divers, or if juveniles are sent through a tube as done e.g. in Great Britain (Bannister and Addison, 1998). However, this strategy was evaluated as the only practical method to release such a large number of juveniles in as short a time as possible. In the period from 1990 to 1994, a total of 128 000 juveniles were released, of which 125 600 were tagged (Table 1). Little was known of the optimal habitat requirements of these juveniles, and emphasis was placed on releasing lobsters in a number of different localities.

Management of the recapture phase

Commercial landings in the release area were closely monitored every year from 1991 for micro-tagged survivors, i.e. lobster above the minimum legal size. All lobsters caught were run through a micro-tag detector (tubular or hand-held wand detector) to identify animals of cultured origin. This was done in close cooperation with fishermen, but also involved personnel from Kvitsøy municipality. This cooperation proved to be extremely fruitful, and since 1995 between 95 and 99 percent of all lobsters caught in these islands have been run through the micro-tag detector. Samples below minimum legal size were also collected, but after recording biological data most of the lobsters were tagged and returned to the sea. However, since 1995 a sub-sample of cultured lobsters below legal size has been taken in order to identify release groups. For each lobster sampled (both above and below legal size) all necessary data were obtained, including time and place of recapture as well as biological measurements. Micro-tagged survivors above legal size were bought from fishermen at market price with an additional bonus of NKr 25.

Genetic monitoring

Cultivation might unintentionally lead to genetic changes in reared animals compared to the wild native population. This has been a problem for most species under domestication/cultivation for stock-enhancement purposes (Allendorf and Ryman, 1987). When the genetic investigations in the Kvitsøy project started in 1991, few genetic studies had been carried out on European lobster. Tracey *et al.* (1975) performed some genetic analyses on the related American lobster and Hedgecock *et al.* (1977) compared the two species. In this stock-enhancement project, using tissue samples of wild-caught lobster, wild-berried females that were used as broodstock, produced offspring as juveniles and as recaptured survivors that have and are still being collected. The analysis is based on genetic variation in enzyme systems as expressed in white muscle tissue. In the early phase of the project, tissue samples from brain, gills, hepatopancreas, heart and eye were collected as well, but as similar results were obtained they were found to be less suitable because the animals then had to be sacrificed. White muscle tissue was collected from one of the periopods or walking legs because these legs will grow back to normal size in one or two growth seasons. The samples were screened by starch-gel electrophoresis using various buffer systems and enzyme staining protocols (Jørstad and Farestveit 1999). Of 22 different stained allozymes, variation was found in only four enzymes: glucose phosphate isomerase (GPI), isocitrate dehydrogenase (mIDHP), phosphoglucose mutase (PGM) and malic enzyme (sMEP). These represent five different enzyme loci, and all main samples collected during the project have been screened with respect to the above-mentioned enzymes.

Fish/crustacean health management

Norwegian law requires that aquatic animals, including lobsters, being transported across regional boarders in Norway have a health certificate to avoid the spread of disease. For this reason, broodstock used in this enhancement project were checked for disease before transport to the hatchery in mid-Norway, and also before they were transferred back to the capture area. The juveniles produced were also subject to the same procedure, and were checked before being transported to the release areas. In the hatchery, the only disease reported was infections with the bacteria Leucothrix mucor, which caused an increase in egg mortality. This bacterium was a problem in only a few instances, and the infection was treated with 1.5 percent Buffodin.

EVALUATION PROGRAMME

Enhancement goals

As described in a previous section, the Norwegian lobster fishery decreased drastically from the 1960s and onwards and has in fact remained at a very low level since the 1980s. The main goal of the stock-enhancement programme was therefore to investigate whether cultivation approaches could increase the overall recruitment in a local stock, and to assess whether the stock could be rehabilitated or at least strengthened on a long-term basis. Another important objective was to evaluate the economic potential of releases of juveniles for sea ranching or private business activities.

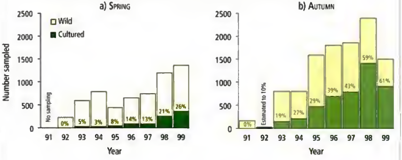
Measures of success

How can success be evaluated or assessed? As pointed out by Cowx (1994) this question must obviously be related to the objectives of stocking, whether it is for enhancement or restoration purposes or for the creation of new fisheries. An important part must involve identification of what contributes to success or failure. In general, strengthening of a stock or population would require cultured animals to survive long enough to reach age or size at maturation and contribute to the overall recruitment. It is also important that the releases should not induce negative effects upon the native stock. An assessment of potential risks should include an evaluation of genetic changes as well as ecological interactions such as evaluation of the carrying capacity of the system, species interactions and control of diseases (Laurec, 1999). In this enhancement project we chose to monitor commercial landings in order to estimate the contribution of cultured lobsters in each fishing season. Given the historical information of previous landings, the carrying capacity is assumed to be unsaturated. We regarded it as important to determine whether cultured lobsters differ from wild and native lobsters with respect to population parameters such as reproduction, growth and survival, as well as to determine whether replacement might have taken place. Measures have also been taken to assess possible genetic changes.

Contribution of cultured lobster to fishery

A sample of commercial landings was collected in each fishing season, i.e. spring (April to end of May) and autumn (October to February, no catches were reported in March). Selected fishermen recorded a representative sample of lobsters below the legal minimum size from their autumn catches. However, in 1997 few fishermen delivered samples below the legal size, and in 1998 very few lobsters could be registered due to lack of sufficient personnel from the Institute for Marine Research (IMR) – the fishing season started with enormous catches and the personnel had to prioritise legal sizes. Above the legal size, the proportion of cultured lobsters in commercial catches has increased since the monitoring programme started in 1991 (Figure 3). There was a clear increase in both the spring and autumn of 1998, when cultured animals made up 21 percent of the spring catches and 59 percent of the autumn catches. Fewer cultured lobsters are caught during spring than autumn, but this merely reflects a different fishing pattern. The lobster pots are set at more weather-exposed parts of the islands during spring, whereas the majority of the releases have been made in sheltered areas that are mainly fished during the autumn (Agnalt *et al.*, 1999). Cultured lobsters have also made up a substantial proportion of the recruiters (Figure 4). An increase was observed until 1996/1997, while a decrease was noted in 1998. This is in accordance with observations of which release groups or year classes are present in the catches related to number released.

FIGURE 3. Sampling of commercial landings of European lobster (*Homarus gammarus*) above legal size at Kvitsøy during (a) spring and (b) autumn, separated into wild and cultured lobster (updated from Agnalt *et al.* 1999). The proportion of cultured lobsters is given above the column. Note that the minimum legal size changed from 22 to 24 cm total length on 1 October 1992, and to 25 cm on 1 October 1993. Data for autumn 1999 are preliminary results because not all information has yet arrived at the Institute of Marine Research



There has been an increase in fishing effort from 1991 to 1999, probably as a result of the enhancement programme. The observed high frequencies of cultured lobsters in the landings could therefore be explained by displacement of wild lobsters in the area. For this reason, some reliable fishermen were contracted to keep logbook of daily catches during the commercial fishing season. Information regarding catches of lobster above and below legal size and the number of lobster pots used was recorded daily. Catch per pot lift was estimated for the five or six fishermen (somewhat variable from year to year) with the highest catches during the autumn fishery, and an average was preferred to simple pooling in order to avoid overemphasising the influence of single data (Agnalt *et al.*, 1999). Since 1995 the same six fishermen have been contracted. Soak time is ignored since 99 percent of the reported catches were made in pots soaked for one or two days, and no differences in catch ability could be found between pots soaked for one, two or three days. Catch per pot lift shows an increase in the proportion of cultured lobsters in the landings, especially in 1998 (Figure 5), as is also shown in IMR's sampling programme. Catches of wild lobster have remained more or less at the same level since 1995. There seems to be a correlation between mean temperature in October and November and autumn landings of wild lobster, although this might also coincide with responses to various stock-management restrictions. The

FIGURE 4. Sampling of lobster below legal size of European lobster (*Homarus gammarus*) during the commercial fishing season in autumn at Kvitsøy (updated from Agnalt *et al.*, 1999). The proportion of cultured lobsters is given above the column. See text for explanation for low numbers sampled in 1997 and 1998

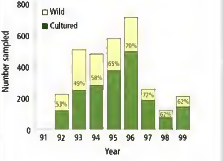
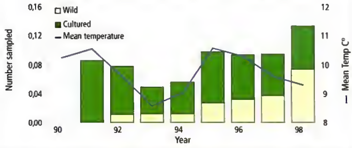


FIGURE 5. Catch per pot lift of lobster above legal size caught at Kvitsøy each autumn season. The catches were separated into wild lobster and lobster of cultivated origin. Note that the minimum legal size changed from 22 to 24 cm total length from 1 October 1992, and to 25 cm from 1 October 1993. The solid line indicates mean surface temperature in October and November at Kvitsøy (data provided by Mr S. Meling, Kvitsøy)



drop in the landings in 1992 and in 1993 is possibly due to a fall in mean temperature, but might also reflect the rises in minimum legal size (MLS) of 3 cm total length (TL), i.e. from 22 to 24 cm TL in 1992 and to 25 cm in 1993. The increase in the catch per pot lift in 1995 is likely to be because of the high sea temperature, but could possibly also be due to an accumulation of recruiters because of the previous years' increase in MLS. A correlation between lobster landings and temperature has previously been noted, e.g. by Dow (1980) and Koeller (1998).

Mr S. Tveite (Institute of Marine Research, Flødevigen Marine Research Station) provided data of catch per pot lift for a variety of locations along the southwestern coast of Norway (Tveite, 1991; Tveite, unpublished data). When pooling this information a very similar exploitation pattern can be seen for wild-caught lobster at Kvitsøy and elsewhere in southwestern Norway (Figure 6). We interpret this as an indication that wild lobsters at Kvitsøy have not been displaced, and that the observed increased landings are due to survival of the cultured lobsters. However, catch per pot lift is lower at Kvitsøy compared to the other areas, and the reason for this has not yet been explored in detail, but might reflect temperature differences. Kvitsøy is located at the outer mouth of a large fjord and is thus very weather exposed, while the other areas are located further south, with generally higher sea temperatures.

FIGURE 6. Number of lobsters caught per pot lift of wild lobsters at Kvitsøy (as in Figure 5), and elsewhere in western Norway (Tveite, 1991, and unpublished data)

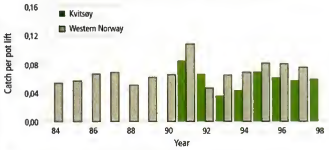
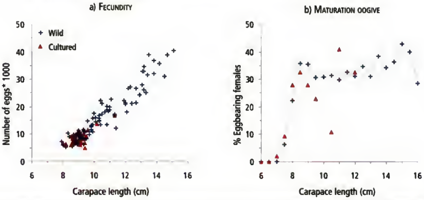


TABLE 2. Summary of lobster-release programmes in Europe. Data from France, Ireland and the United Kingdom are from Gendron (1998). All release programmes, except the one in Norway, ended when recaptures reached zero. The recapture period in Norway includes data until 31 December 1999. Recaptures could not be reported on two occasions since the released lobsters were too small to be tagged

Country	Release year	Recapture year	Number released	Age at release	Number recaptured	Number of berried females	Total recapture %
France	73–83		100 000–225 000	2–3 weeks			
France	84–87	87–89	25 480	~1 year	22		
Ireland	93–97		292 000	2–4 weeks			
UK	83–88	88–93	49 128	~1 year	653	18	1.3
UK	84–88	88–94	19 233	~1 year	453	20	2.4
UK	84–90	85–93	3044	~1 year	58		1.9
UK	84–89	85–93	19 520	~1 year	307		1.6
Norway	90–94	92–99	127 945	~1 year	6766	950	4.9

A total of six year-classes were released during the five-year period from 1990 to 1994. The releases in 1990 consisted of two year-classes, (88 and 89), that appeared for the first time in the commercial landings in autumn 1992. In the two years since the release, the lobsters had grown from a release length (TL) of 3 to 6 cm to a recapture length of 23 to 25 cm. They had also obtained a body weight of 400 to 500 grams in this short time period. The so far largest recaptured lobster weighed 1.9 kg. The highest recapture percentage obtained is 9.4 percent for the 89 year-class, whereas recaptures of the 90 and 91 year-classes dominate in terms of numbers (Table 1). The 92 and 93 year-classes have commenced to recruit to the fishable part of the stock. Since they made up 35 percent of the total number released, and samples below legal

FIGURE 7. Differences between cultured and wild female lobsters with respect to (a) fecundity (samples collected during autumn 1996 and spring 1997) (Agnalt, unpubl. a) and (b) maturation ogive (data pooled from autumn 1991 to autumn 1998 to avoid year-class differences; each point is based on a minimum of five observations) (Agnalt, unpubl. b) in comparison with a reference sample of wild lobsters collected during the same fishing season. The results clearly demonstrate that significant genetic changes in allele frequencies, even as small as those observed here, are also likely to occur in lobster cultivation. As in other species the risk of unwanted changes is clearly dependent on the numbers of broodstock actually used (genetic drift), and in differences between wild and farmed environment (selection)



size confirm survivorship, recapture is expected to increase in the years to come. By autumn 1998 all year classes are present in samples above legal size, although the first and the last (88/89 and 93) have been found only in small numbers. At Kvitsøy, about 21 700 lobsters had been checked by 31 of December 1999 for cultured survivors, and among these 6 538 released individuals were identified. This means, an overall recapture percentage of 5.1, but this will increase as the recapture period has not yet ended. The monitoring programme will continue until 2001. The present recapture percentage is already substantially higher than in other release projects elsewhere in Europe (Table 2). With respect to berried females of cultured origin, 980 individuals have been caught at Kvitsøy, compared to only 20 in the four release areas in the United Kingdom of Great Britain and Northern Ireland. None of the other enhancement studies has included estimates of tag loss into final recapture rates. We have partly accounted for some of the tag loss by including lobsters that developed double scissors claws during the nursery period and for unknown reasons thereafter lost their tags.

The possibility of out-of-area migration has been considered in the project, and catches from five to six locations in the surrounding areas to Kvitsøy have been investigated every autumn season since 1995. So far, no micro-tagged survivors have been detected in these surrounding areas.

Interaction with natural populations

As the main goal of the programme is to strengthen a stock on a long-term basis, it is important to evaluate if there is a contribution made by the cultured animals to the total reproduction of the stock concerned. Emphasis must also be placed on evaluating possible interactions with native lobsters, and assessments of population parameters such as maturation, growth and survival must be made.

Studies of the number of eggs produced by wild and cultured females were made in autumn 1996 and spring 1997, and no differences could be found between cultured and wild females (Figure 7a). However, cultured lobsters had not yet grown to sizes larger than 12 cm carapace length. The maturation oogive shows similar patterns of maturation for wild and cultured animals, although in the maturing phase there is tendency towards a higher percentage among cultured females at each length group (Figure 7b). For larger sizes a lower percentage among cultured females probably describes the reproductive status of one or two year-classes rather than the average. On the other hand, wild females are represented as a pool of an unknown number of year classes. The production cycle means that not all females reproduce every year, and therefore there is no length group in which all females are berried at the same time. Furthermore, berried females of cultured origin have been present in landings since 1993, and since 1995 they have made up a significant proportion of the total number of berried females caught (see figure 28.5 in Agnalt *et al.*, 1999). A tagging experiment started in July 1996, focusing on growth and survival. Recaptures obtained so far indicate a higher growth increment at each moult in males than in females, though so far there are no differences between wild and cultured animals. More information is being collected to confirm or reject this trend. It has been shown that with the present MLS of 88 mm CL, all female lobsters have spawned once before capture, and a majority have done so twice.

Morphological differences between cultured lobsters and their wild conspecifics have been found. Preliminary investigations of claw morphology indicate that cultured lobsters have developed slightly longer claws (both crusher and scissors), and females of cultured origin have a tendency to be smaller or slimmer in the second abdominal width (applied as a secondary character to evaluate onset of maturation). It must be pointed out that this analysis is still at a preliminary stage. In addition, Agnalt *et al.* (1999) reported that lobsters with double scissors claws were more prone to be caught than animals with the normal set of one crusher and one scissors claw.

Genetic aspects

The results of the analyses of tissue samples collected from wild lobsters, wild lobster broodstock and offspring as juveniles have been tested with respect to possible genetic changes in the last three production years, i.e. 1992, 1993 and 1994. For the 1992 production, from which juveniles were released in that year, no genetic changes were found in allele frequencies at any of the allozyme loci when all three samples were tested. Pairwise testing revealed small but statistically significant differences between the produced juveniles and the reference sample taken from the wild population. For the 1993 production no significant genetic changes were found in any of the loci investigated. However, for the last juvenile production in 1994, both the wild broodstock and the juveniles later produced. The results clearly demonstrate that significant genetic changes in allele frequencies, even as small as those observed here, are also likely to occur in lobster cultivation. As in other species the risk of unwanted changes is clearly dependent on the numbers of broodstock actually used (genetic drift), and in differences between wild and farmed environment (selection).

Economic analysis (cost/benefit)

During recent years some attention has been given to evaluations of economic aspects of sea ranching and marine stock-enhancement projects (Moksness and Støle, 1997; Hilborn, 1998; Moksness *et al.*, 1998), but very few species or stocking programmes have been found to be economically viable. Within the PUSH programme economic analyses have been regarded as important goals. The lobster stocking project applied the software package Powersim® (Cover 1996), and the simulation model was called LOBST.ECO that is described in more detail by Borthen *et al.* (1999). There are separate modules for wild and cultured lobster, and males and females are separated for each variable. Since cultured lobsters make a substantial contribution to the overall reproductive potential at Kvitsøy, it was considered essential to evaluate the "secondary" effects when cultured lobsters reproduce once. The simulation model was also employed to analyse possible biological responses to stock management restrictions such as a spring-fishery ban and an increase in MLS of 2 cm. For these results we refer to Borthen *et al.* (1999).

Two distinct economic perspectives were evaluated:

Public – Cultivation procedures along with releases are publicly managed. Harvesting can be organized either in terms of free access to the fishermen or by allocating limited access, if necessary with a fee;

Private – The releases are organized as private enterprises, with exclusive rights to harvest.

If the releases were privately run, approximately 25 percent would have to be recaptured to cover the costs of inputs and capital. Preliminary estimates at Kvitsøy indicate that 14 percent of the first release group in 1990 can potentially be recaptured, while the other release groups are in the process of recruiting to catchable sizes. The estimates can only be confirmed when all groups have reached catchable sizes. There are indications that predation pressure is particularly high during a brief period just after release, and several suggestions have been made as to how to protect the juveniles against predation. However, in large-scale releases these methods might prove too expensive. If the releases are in the public sector their socio-economic value depends on the value of recaptures of cultured lobsters, the value of recaptures from the next generations (offspring), and the value of the increased or "saved" lobster stock in the situation when the stock was very low before the enhancements started. Preliminary estimates show that an improvement in catch from the second generation can be of the same order as the gain from the first (14 percent + 14 percent), if overall recruitment increases in proportion with the increase in the spawning stock. This assumption has not so far been proven and is still unresolved. A substantial increase in the reproductive potential of, and possibly also recruitment to, the enhanced lobster population has been suggested on the basis of information about the frequencies of berried females of cultured origin in the landings supplied with fecundity data.

Moksness *et al.* (1998) applied a net-present value approach in their analysis based on data from the large-scale release experiments described in this paper, though in an earlier phase. They concluded that sea-ranching lobster would be viable if juvenile costs could be reduced to 6.6 NKr or US$0.85 (exchange rate on 1 September 1999) and if 15 percent of the cultured lobsters were recaptured. LOBST.ECO is more complex and goes one step further by including first-generation offspring. Given the information available from Kvitsøy this approach is more in accordance with reality. Hilborn (1998) evaluated the release experiment in the United Kingdom of the United Kingdom of Great Britain and Northern Ireland on the basis of information obtained from Addison and Bannister (1994) and concluded that with recovery rates between one and two percent this programme was far from economically viable. He did not indicate which recapture percentages would make these release experiments viable.

The lobster hatchery at Kyrksæterøra in mid-Norway closed several years ago, but a Norwegian company, Norsk Hummer AS, plans to build a new large-scale hatchery at Tjeldbergodden, also in mid-Norway. The annual capacity is estimated to be 1.2 – 2.4 million juveniles, and potential customer groups include sea-ranching enterprises (public, semi-public or private) in Norway and abroad, aquaria and, in the long run possibly also intensive cultivation companies. Where the last group is concerned, cannibalism is believed to be the major obstacle to further development. It is believed that each young lobster needs separate compartments, which is very demanding of space and human resources as well as being costly. Preliminary experiments with communal rearing performed at a local hatchery at Kvitsøy in 1998 and 1999 have given promising results as regard to survival, growth and density (Jørstad *et al.*, 2001). These experiments will continue aiming to produce juveniles for release purposes as well as lobsters for consumption. With good results one may expect to see lower prices that would improve the financial results in both sea ranching and intensive lobster farming.

Associated management strategies

In 1998 a new pilot project commenced at Kvitsøy with the aim of evaluating the feasibility of a ban on landing berried females. Local fishermen at Kvitsøy and the Directorate of Fisheries in Rogaland took the initiative, but IMR is also involved. All berried females, whether wild or cultured, are currently bought from fishermen, and when the fishing season is over these females are released at particular sites around the islands. The idea is to see if this can contribute to an overall increase in reproductive potential and strengthen recruitment on a long-term basis. The local police force is also involved to reduce illegal fishing that peaks during the summer. The experience is without doubt very positive. The fishermen are eager to deliver berried females, and they say that efforts to combat illegal fishing are crucial for the stock.

In a depleted local lobster stock such as the one at Kvitsøy, heavy fishing pressure on cultured lobsters when they reach MLS will only result in a short-term increase in harvest. This implies that annual releases must continue to maintain harvesting levels. Clearly, a more sustainable strategy should include approaches that aim to restore the local stock to previous levels of recruitment, and this will only be possible with the introduction of new approaches to management. In that respect the need for cultivation projects can be regarded more as a temporary activity which can be reduced when stocks reaches an acceptable level.

Atlantic cod *(Gadus morhua)*

REVIEW OF FISHERY

The Atlantic cod has a wide distribution and is found on both side of the Atlantic Ocean, and the different stocks have distinct life history characteristics and migration patterns (Jakobsson *et al.*, 1994). Atlantic cod captured on the Norwegian coast are separated into Northeast Arctic cod and coastal cod. The Northeast Arctic cod is a large stock that makes long spawning migrations from its feeding areas in the Barents Sea to the spawning grounds at Lofoten and along the Norwegian coast (Bergstad *et al.*, 1987). Coastal cod, found along the entire coast, are much fewer in numbers and are mainly stationary (Svåsand and Kristiansen 1990). The two groups can be distinguished by both meristic and genetic characters (see references in Svåsand *et al.*, 1996).

Coastal cod were used for the releases in Norway. Catch statistics are available for coastal cod for the area north of 62° N for 1985–97 (Figure 8a), and for the area south of 62° N for 1977–98 (Figure 8b). Whereas catches in the northern part of Norway varied between 25 000 to 75 000 tonnes, registered catches in the southern part were less than one tenth of that quantity. Even taking into account that a large part of the total catches in the southern part of Norway probably are taken by sports fishermen, it must be concluded that total quantity of coastal cod in this area is small. The increasing interest in cod stock enhancement in the late 1980s coincided with both small catches of coastal cod and a crisis in the fishery for the Northeast Arctic cod stock. For fishermen and the fishing industry the latter stock was of greatest importance, and the total catch of Northeast Arctic cod fell to a minimum level in 1990, with total catches of only 187 000 tonnes in 1990, of which only 89 000 tonnes were captured in the Norwegian fishery (Anon., 1999).

REVIEW OF PREVIOUS CULTIVATION PROJECTS

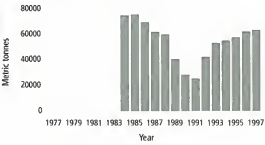
In 1864, G.O. Sars discovered that cod has pelagic eggs and he managed to hatch the eggs (Sars, 1879). This made marine stock enhancement possible. Captain G.M. Dannevig, who founded the Flødevigen Hatchery in 1882 followed up Sars' findings and released the first larvae in 1884. Parallel activities were initiated in the United States and Canada (Shelbourne 1964, Solemdal *et al.*, 1984). During the final quarter of the nineteenth century, the development of steam-powered fishing vessels greatly increased fishing power in the North Atlantic fisheries, and both fishermen and politicians soon became concerned about overfishing (Kirk, 1987). Artificial production and release of cod larvae were stated as a means of solving this problem, and the hatchery boom continued for nearly 90 years, mainly in Norway and the the United States. The hatchery period has already been thoroughly described and discussed by Shelbourne (1964) and Solemdal *et al.* (1984).

The last releases were conducted at Flødevigen in 1971 (Solemdal *et al.*, 1984), and a century of cod larvae releases were stopped without any definite evidence of benefit (Tveite, 1971). Later experimental releases of genetically marked yolk-sac larvae have shown that the potential benefits of releasing yolk sac larva are actually very small (Kristiansen *et al.*, 1997).

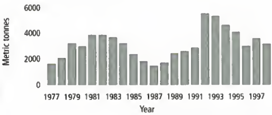
In Norway releases of cod were re-established on a small scale in the mid-1970s and on a large scale from the mid-1980s, but this time with larger more viable cod juveniles (>10 cm). In 1985 the Research Council of Norway initiated an interdisciplinary research programme on sea ranching of cod (Cod in Fjords) with experiments in several fjords along the coast (Svåsand, 1998). This programme was further scaled up in 1990 when the Norwegian government decided to establish a programme for the development and encouragement of sea ranching (Norwegian acronym: PUSH).

FIGURE B. Catch of coastal cod along the Norwegian coast.
a) Catch in the area north of 62°N (Berg, Eriksen and Eliassen, 1998), and b) catch in the area south of 62°N (extract of data from Directorate of Fisheries; T. Jakobsen (personal communication, 2000), Institute of Marine Research). The catch statistics only cover catches from registered fishermen

b) North of 62°N



a) South of 62°N



The main aims of the new programme were to develop full-scale production of cod juveniles, techniques for mass marking, and to design and conduct large-scale release experiments on the Norwegian coast, in conjunction with extensive field studies aimed at clarifying the potential for profitable sea ranching. A further aim was to determine whether releases of juvenile cod could even out the natural fluctuations in recruitment in cod stock and thereby stabilise the fisheries.

METHODOLOGY OF SEA RANCHING

Broodstock selection and management

For the main releases, the broodstocks used for production originated from wild fish collected from the release regions. Both wild captured cod and offspring of wild fish were used as broodstock. However, no breeding programmes have been undertaken so far. County veterinary health regulations require captured wild fish to have a health certificate before they may be transported to the production site in order to ensure that the broodstock is healthy, and to prevent the spread of pathogens. Similar procedures are required for the transport of fish from one farm to another, and for juvenile fish before release.

Cod readily spawn in captivity, and both spawning pens and spawning tanks were used to produce fertilised eggs. A female cod in good condition can produce about one litre of eggs per kilogram body weight during the spawning season (Holm *et al.*, 1991). In Norway cod spawn from late February to April. After spawning the fertilised eggs are transferred to a hatchery where they hatch after two to three weeks depending on the temperature. Mortality during the hatching period is around 50 percent, and 200 000 to 300 000 larvae normally survive from each litre incubated. However, large variations are found.

The newly hatched larvae are transferred to different types rearing facilities, such as large seawater enclosures (Figure 9), plastic bags or tanks where they are startfed on live plankton, mainly wild. In some cases cultured algae, rotifers and Artemia were also supplied (Anon., 1995). Semi-natural systems have several drawbacks. The main bottleneck is that production is based on the natural production of plankton, which varies according to seasonal and local variations caused by changes in wind directions and other parameters. Toxic algae or pathogens in the surrounding waters can also influence an open system.

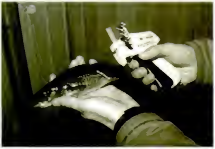
On the other hand, we know that reared fish ought to be as natural as possible in order to ensure a high survival rate after release. The development of phenotype and behaviour is influenced by genetic characteristics and environmental parameters (Svåsand *et al.*, 1998b). It is therefore no surprise that cod reared in a natural systems look like wild cod (similar phenotype), and it may be concluded that pond-reared cod are quite fit for release into the wild.

Tagging method and release strategy

Efficient tagging methods had to be developed before the effects of fish released could be evaluated. For the releases in Norway several types of external tags (T-tags, Figure 10), chemical marks (oxytetracycline and alizarin complexone) and genetic marks (rare genotypes) were used depending on the purpose of the releases. Further

FIGURE 9. Parisvatnet – the main location for production of juvenile cod in Western Norway. The production unit is a field station run by the Institute of Marine Research in Bergen. The right-hand photograph shows the seawater enclosure (50 000 m^2, 270 000 m^3). When the cod fry reach a size of about 1 g a dip net is used to collect the fry from the enclosure (left)

FIGURE 10. Use of T-tags was the main external tagging method used on cod in Norway. These tags can be used on cod larger than 14–15 cm



details are given in Otterå *et al.* (1998), Svåsand (1998) and Svåsand *et al.* (1998a, b). Use of internal marks requires fishing surveys because these marks are not visible on the outside of the fish. The advantages of these marks are that they are inexpensive, have high tag retention and are easy to apply on large groups of fish. To study migration and when information from fishers is needed, T-tags (Floy anchor tags and T-bar tags) were used. These tags can be used on fish larger than 14–15 cm. Otterå *et al.* (1998) provide further details on tagging cod with anchor tags. In most cases the cod were transferred from the rearing unit to the release area by well boat or in tanks in a small boat. Fresh seawater or O_2 were supplied as necessary. At the release sites the juveniles were released into shallow water. During the release programme different release strategies were tried, and the effects of acclimatisation were tested. The mean sizes at released varied between 8–41 cm (Svåsand *et al.*, 1998a).

Management of the recapture phase; ecosystem analysis

All released fish were tagged or marked. A recapture programme followed up the main releases, and extensive ecosystems analyses were carried out in two of the release areas (Masfjorden/Øygarden) in western Norway and Stålvikbotn, Ullsfjord and Sørfjord in Troms (Svåsand *et al.*, 1998a).

In order to obtain information about recaptured fish from fishermen and sports fishers, the release programme was advertised in local newspapers, and pamphlets and registration forms were sent to local households and placed in post offices and groceries in the release area. A reward of 25 NKr was paid for each returned tag.

Genetic monitoring

Genetic studies using haemoglobin and five enzymes; LDH, GPI, PGM, GPD and IDH, were incorporated in the different releases in western Norway, and several aspects were studied (Jørstad *et al.*, 1994, Jørstad *et al.*, 1999, Svåsand *et al.*, 1998a). Besides genetic monitoring to detect any unwanted genetic changes, genetic marking was used to distinguish released fish from wild cod. More than 280 000 genetically marked juvenile cod (homozygous for a rare allele; GPI-1*30). were released in Masfjorden and Øygarden, western Norway. Genetically tagged yolk-sac larvae (18 million) were released in Heimarkpollen, Austevoll, south of Bergen in 1995 (Kristiansen *et al.*, 1997) and genetic analyses were later used to detect released fish.

EVALUATION PROGRAMME

The cod stock enhancement during the PUSH programme was conducted in the following main areas: Austevoll, Øygarden, Masfjorden in Western Norway, Ytre Namdal in mid-Norway, and Vestfjorden and Troms in Northern Norway, and a total of 720 000 reared cod (mainly 0 and 1 groups) were tagged and released between

1990 and 1996 (Figure 11). Several of these releases were prolongations of earlier enhancement programmes, and a total of 1 million juvenile cod have been released on the Norwegian coast since 1977 (Svåsand *et al.*, 1998a).

The following sections summarise the principal results and conclusions of sea ranching cod during the PUSH programme and are based primarily on Svåsand (1998) and the results reported in the final report to the Research Council of Norway (Svåsand *et al.*, 1998a). A more comprehensive review has recently been published in a primary journal (Svåsand *et al.*, 2000).

Sea-ranching goals

According to Svåsand *et al.* (1998a) the principal aims of the programme were to develop full-scale production of cod juveniles and techniques for mass marking, and to design and conduct large-scale release experiments on the Norwegian coast, associated with extensive field studies to identify the potential for profitable sea ranching.

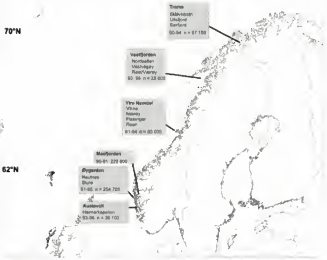
MAIN RESULTS AND CONCLUSIONS

Production

The production methods were further developed during the PUSH programme, and a total of nine projects produced 1.2 million cod fry in the period 1990 to 1995. Sufficient numbers of juveniles were tagged and released to test the main aims of the programme (Svåsand *et al.*, 1998a, 2000, Figure 11).

Exposure to an artificial environment during ontogeny might affect both phenotype and behaviour, and thereby also affect survival rates after release. Few differences were

FIGURE 11. Map showing releases of reared Atlantic cod in Norway in the period 1990–1996 (based on data from Svåsand *et al.*, 1998a)



found between reared and wild cod after release, and this was attributed to the use of a semi-natural rearing environment. However, the reared cod needed some weeks after release to acclimatise to the wild environment, and it was also clear that the time in the artificial rearing environment was of some importance. (For further discussion see Svåsand *et al.*, 1998a, 1998b, 2000).

Genetic monitoring

Apart from the genetically marked fish, the results show few genetic differences between wild and released fish in the same area. In some cases the unexpected frequencies of genotypes found could be attributed to genetic drift possible caused by an inadequate number of fish in the spawning pens. However, these conclusions are based on a small part of the cod's genome. For further details and discussion, see Jørstad *et al.* (1999).

Migration

Most of the released cod were recaptured in the vicinity of the site of release. Of more than 7 000 recaptures more than 70 and 90 percent were taken less than 5 and 10 km respectively from the place of release. However, both geographical variation and increased dispersion with size were found (Svåsand *et al.*, 2000).

Recapture

Large variations were found in the reported recapture rates from the different main release areas in Norway, varying from 0 to 15 percent for cod released as 0 and 1-groups (Figure 12). A general trend was a correlation between size at release and reported recapture rates, but release season also influenced the results.

Natural mortality was high in fish smaller than 20–30 cm (depending on release area). The cod recruited early to the local fishery, especially in southern Norway, and were heavily exploited while they were still small. Thus, most of the recaptures were recaptured as small fish, giving a low recapture biomass, even with relatively high recapture rates. The reported recapture yield was smaller than the released biomass for most of the experimental releases, as illustrated by the releases in Øygarden in

FIGURE 12. Reported recaptures from different size groups of cod released in the main release areas in Norway (drawn from data in Svåsand *et al.*, 1998a)

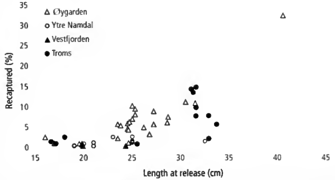
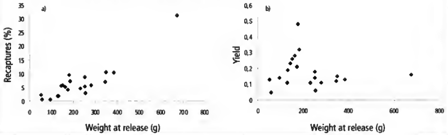


FIGURE 13. Reported recaptures (a) and yield (biomass of recaptured fish/biomass released) (b) from selected releases in Øygarden (drawn from Otterå *et al.*, 1999)



western Norway (Figure 13). However, when evaluating the results it is important to account for unreported recaptures and loss of tags. When 10 percent tag loss (Otterå *et al.*, 1998), and a reporting rate of 41 percent in the Øygarden area (Otterå *et al.*, 1999) are taken into account, nearly all the results were still negative. Similar results were obtained in other areas. Mortality and recapture patterns of released cod are further discussed in Svåsand *et al.* (1998a, 2000) and Kristiansen *et al.* (2000).

Economic evaluation

Economic profitability could not be obtained with current costs of producing cod juveniles as well as other financial constraints (Svåsand *et al.*, 1998a, 2000). As shown above, the biomass of the recaptured cod was simply too low. Increased fishing pressure due to recreational fishery and tourism on the local fishery resources however, could make releases of cod a method of attraction tourists. Such a concept could involve the release of large (30–40 cm) cod in the vicinity of tourist attractions on the coast or in the fjords. Cod of this size have low natural mortality, and most of the fish would stay close to the release area. Releases of such "large" cod have previously resulted in recapture rates above 50 percent.

There is currently a growing interest in net-pen rearing of Atlantic cod, due to new knowledge about more effective rearing methods, using light to postpone the time for maturity and increased growth, and better prices for cod in Norwegian and European markets. Given the economic constraints of today, and new biological knowledge, interest in Atlantic cod has shifted during the 1990s from stock enhancement to net pen rearing.

Evaluation of new knowledge

Cod stock management activities in Norway have resulted in a wealth of new information, and the final report from the PUSH-programme (Svåsand *et al.*, 1998a) refers to 13 M.Sc. dissertations, six Ph.D. theses, and more than 60 refereed publications that deal with various aspects of the scientific basis of stock enhancement.

This unique knowledge, which is now published in a refereed journal (Svåsand *et al.*, 2000), will be of importance both for the further development of stock enhancement in Norway and also as a basis for evaluation of marine species stocks in other countries.

Implication for management

There have been no changes in the management of coastal cod resources during the programme period. Today there are minimum size limits for sales of cod; 47 cm north of 64° N, and 30 cm south of this 64° N. For fishing for one's own household there are no size limits, only a limitation in the amount of fishing gear permitted (max. 210 m fishing nets, 300 hooks, and 20 pots or traps). Foreign citizens may take part in sports fishing with hand-held tackle, but may not set out fixed equipment, and they are not allowed to sell their catches. Nor are Atlantic cod included in the new proposal for an Act on sea ranching, as this will deal only with molluscs, crustaceans and echinoderms.

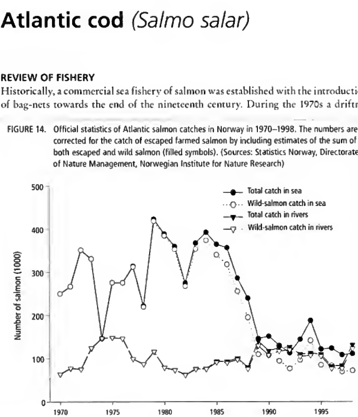
As shown above, a great deal of the new knowledge that has been obtained during the programme is relevant for the future management of coastal cod stocks, as well as for other important coastal resources. It is likely to take some time as well as further treatment of the data before this new information can be incorporated in the management of wild cod stocks.

Atlantic cod *(Salmo salar)*

REVIEW OF FISHERY

Historically, a commercial sea fishery of salmon was established with the introduction of bag-nets towards the end of the nineteenth century. During the 1970s a driftnet

FIGURE 14. Official statistics of Atlantic salmon catches in Norway in 1970–1998. The numbers are corrected for the catch of escaped farmed salmon by including estimates of the sum of both escaped and wild salmon (filled symbols). (Sources: Statistics Norway, Directorate of Nature Management, Norwegian Institute for Nature Research)



fishery developed. Until the ban of this fishery in 1988, the number of salmon caught in the sea was clearly higher than the river catches. During the 1900s sea-catches of wild salmon were comparable to those in rivers (Figure 14). The numbers of salmon caught in rivers has been relatively stable since 1970. However, new regulations and improved salmon management have probably improved the statistics and mask a probable decline in many stocks during this period.

REVIEW OF PREVIOUS CULTIVATION PROJECTS

In the 1750s Jacobi from Germany was the first to hatch eggs of freshwater fish, but at the same time the Norwegian Jakob Sandungen was apparently carrying out similar experiments (Sømme 1941). Releases of larvae and juveniles expanded in Norway during the 1850s and several hatcheries were built, mostly to produce trout but also for salmon and Arctic char. An important part of this expansion can be traced back to public funding and the establishment of public inspections of the freshwater fishery. The extent of salmon larvae releases increased considerably when an export duty was introduced, and in the 1940s releases of salmon reached the level of trout releases. Between six and seven million salmon larvae were released as opposed to eight million trout. The larvae were released shortly after hatching because it was believed that natural mortality was highest in eggs. The purposes of these releases were to stabilise the stocks, increase the fishery and to introduce fish to lakes that had previously contained few or no fish.

In United States it was common as early as the end of 1800s to produce older juveniles in order to further reduce natural mortality. In the early 1900s most other countries in Europe had adapted this method while in Norway it did not become common practice until the 1970s. The most common strategy was and still is to release fish that have hatched in the spring, fed for a few months and then released during the summer. The number of smolts produced increased from about 250 000 in 1970 to one million at the end of the 1980s.

In Norway most of the stocking programmes took place in rivers and watercourses that already contained natural and wild salmon populations. In other countries the focus was on other kinds of releases, localities and purposes. In Iceland, for example, a research station was build in the early 1960s to produce salmon for release into small rivers or watercourses that did not already have natural wild salmon populations. In the 1980s, a "sea ranching stock" was built up to produce smolts for commercial release projects. Recapture rates were high at the release locations, frequently above 5 percent during the 1980s, however recaptures decreases for unknown reasons in the 1990s. Prices also fell at the same time and today the Icelandic fish-stocking industry has closed down.

In Norway work was done with tagged salmon smolts, which were released to study smolt behaviour, migration and adult returns. A research station that was operational in the River Imsa since the early eighties compared the performance of wild and cultured smolts in a number of experiments (Jonsson and Heggberget, 1993). Knowledge of freshwater rearing practises and smoltification was being accumulated in parallel with the buildup of a substantial farming industry in Norway. There was political will to stimulate the development of sea ranching in coastal areas due to the ban of the driftnetting fishery in 1988. This fishery, which was an important component of fishermen's income in many coastal communities, was responsible for most of the catches in the sea until 1988 (see Figure 14).

METHODOLOGY OF SALMON SEA RANCHING

The following section summarises the principal results and conclusions from the salmon sea ranching projects during the PUSH programme, and is primarily based upon preliminary results reported in the final report to the Research Council of Norway (Skilbrei *et al.*, 1998).

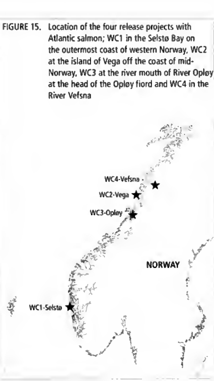
Sea ranching models and release sites

Four different release sites were chosen for sea ranching Atlantic salmon. The intention was to test different sea ranching strategies and to compare localities that differed with respect to size of the watercourse and distance to open sea. The projects mostly released smolts, but yolk-sac fry were released in one of the projects. For the sake of simplicity, the projects are termed according to the size of the watercourse at each location. They are called WC1, WC2, WC3 and WC4, where WC1 denotes the smallest watercourse, and WC4 the largest.

Project WC1

Smolts were released from net pens into a small marine bay located on the outer coast of western Norway (see Figure 15). A small watercourse of 1.5 km^2 basin drains to the bay. Most of the freshwater runs through a small hatchery close to the bay in which the smolts were kept prior to release. The watercourse (a brook) was much to small to support a wild salmon stock, and it could not be entered by returning adults that were caught in the bay by gillnets. A monitoring programme was developed to estimate catches of sea-ranched salmon by the nearby bag-net coastal fishery for migrating salmon. Between 40 000 and 55 000 smolts were released annually for three successive years, 1992–1994.

FIGURE 15. Location of the four release projects with Atlantic salmon; WC1 in the Selstø Bay on the outermost coast of western Norway, WC2 at the island of Vega off the coast of mid-Norway, WC3 at the river mouth of River Opløy at the head of the Opløy fiord and WC4 in the River Vefsna



In WC1 the primary goal was to develop methods for sea ranching from a small watercourse located on the coast. The rationale was that such locations maximise the distance to, and hopefully minimise the interactions with, natural populations that are usually to be found in fjord areas. In addition, survival was expected to be high as there are a number of species that prey on the wild smolts from the time when they leave the river mouth and migrate through the fjord region. Emphasis was put on detailed studies of stock and family variations, release methods and geographical distribution of adult catches.

Project WC2

This project was located to the island of Vega, close to the outlet of a river draining a basin of approximately 20 km^2. A small grilse stock spawns in the river. The smolts were transferred from a mainland hatchery to net pens close to the river mouth prior to releases. After a small release of 7 400 smolts in 1991, 74–136 000 smolts were released every year from 1992 to 1995 except in 1994, when most of the smolts were killed as the result of a technical accident. Anglers in the river caught some returning adults, but most were caught in bag-nets and gillnets in the sea close to the mouth of the river. Project WC2 was also located on the outer coast (an island), but its emphasis was on releasing large numbers of smolts in order to simulate a situation that would resemble a commercial ranching operation. One reason for this approach was the explicitly stated political goal of identifying new sources of income in coastal regions after the ban of the coastal driftnet fishery for salmon in 1989. In addition, promising results had been obtained from similar project in Iceland during the 1980s.

Project WC3

The project was located on the Opløy River in the head of the Opløy Fjord in mid-Norway (Figure 14). The smolts were released in the river mouth close to the sea or from net pens in the estuary of the river. Salmon are prevented from entering the main course of the river by a hydroelectric power plant. Returning salmon were caught by a combination of bag-nets in the inner part of the fjord, angling in the estuary and lower 300 m of the river and catches in a trap in the lowest part of the river. From 1989 to 1996 a total of 558 000 smolts were released. The Opløy River is large enough to sustain a sports fishery for returning salmon in the river mouth. By including the recreational angling approach it was assumed that anglers would be willing to pay a higher price per fish compared with commercial market prices for salmon, thereby increasing the profitability of the project. The project was therefore organized in cooperation with local interests that administrated the fishery; sale of fishing licenses, accommodation etc. An intensive tagging programme was implemented in order to gain basic knowledge relevant to the further development of the project, for example to provide an economic analysis with data for estimating the costs and benefits of this sea-ranching model.

Project WC4

Unlike the other projects, WC4 was located in a large river that supports a wild salmon population; the River Vefsna. The project compared two different strategies; 1) releases of unfed fry in the upper tributaries of the river Vefsna that are not naturally reached by salmon, and 2) releases of smolts in the lower reaches of the river. In small lakes and rivers in the three upper tributaries approximately 150 000 fry were released every year, and traps for migrating smolts were built to measure the production potential in these areas. Between 1992 and 1995, a total of 58 310 Carlin-tagged one- and two-year-old hatchery-reared smolts were released, and in 1987–1995 a total of 10 512 wild smolts were captured and tagged for comparison.

The main goals of project WC4 were to study the potential for sea ranching and to reinforce the River Vefsna stock. Vefsna used to be an important salmon river, but production has dropped dramatically due to the introduction of the salmon parasite *Gyrodactylus salaris*. In that respect, the releases of fry in the upper tributaries are comparable to an enhancement programme. One important objective for the releases of hatchery-reared smolts in the main river was to compare the survival rate of these fish with the adult returns of Carlin-tagged wild smolts (originating from the fry releases) and with the hatchery smolts of the same hatchery stock released on the outer coast in project WC2.

BROODSTOCK SELECTION

The broodstock were taken from the same region as the intended release area, since salmon stocks from different regions may have different migration patterns, feeding area and ecological preferences. In this way, fish that stray can be expected to enter nearby rivers and will then belong to the gene pool of that area. Brood fish were also selected according to background information regarding the age and size of returning wild fish, since such factors influence the outcome of sea-ranching operations.

For the three stocking projects in mid-Norway (WC2, WC3 and WC4) multi-sea-winter stocks were chosen because large salmon are more valuable than the grilse component returning after one winter in sea. In project WC3 the size of the brood fish varied from 7 to 12.5 kg. The size of the brood fish in project WC2 and WC4 was from 6 to 7 kg. As mortality is expected to increase with the duration of the stay in the sea, several stocks were tested at the southernmost release site, project WC1. A typical grilse stock in which the adults rarely reach weights above 2 kg, a stock composed of both grilse and multi-sea-winter salmon (1.5–10 kg) and finally a stock known for its large size, were selected. In the last case, females were between 5 and 12 kg, while males ranged from 1.5 to 13 kg.

In project WC3 the brood fish were caught in bag nets in the sea close to the river mouth of the large River Namsen in midsummer and kept in net pens until late September when they were transferred to hatchery tanks supplied with running freshwater and stripped in late October. In the other projects brood fish were sampled from the spawning grounds from September to November.

Rearing of young fish

Except for the releases of unfed fry in WC4, smolts were produced according to standard production regimes of commercial hatcheries (see e.g. Edwards 1987). In WC3, smolts were bought from a commercial hatchery. In WC2 and WC4 a hatchery was taken over to produce smolts for releases purposes only. In WC1 the first generation of smolts was produced at the hatchery at the release site, operated by the Institute of Marine Research, while the following two year-classes were produced by a commercial hatchery. In order to study family groups, they were kept separated in relatively small tanks of 1×1 metre, during the early development stages, and transferred progressively to larger tanks (2 to 8 m diameter) when they had grown large enough to be tagged.

Tagging method

Several tagging methods were employed; microtags, visible implant tags and adipose fin-clipping, Carlin tags were used most frequently. This external tag has been utilised in salmon research in Norway for several decades and is therefore familiar to the public; hence the likelihood of receiving tags from the sea-fishery for migrating salmon and from anglers in rivers, especially when the fish are caught far from the release site, is higher for this tag. However, attaching the tag to the fish by two thin metal wires just below the dorsal fin may be harmful and probably increases post-release mortality. This problem is probably most serious when tagging 1+ smolts, as they are usually smaller than 2+ smolts. Unreported tags contribute to bias survival rates. Comparisons between recaptures of adipose fin-clipped and Carlin-tagged adults at the release sites in WC1 and WC2 indicate that 1+ return of Carlin-tagged fish are approximately 30 percent lower. For individually tagged cod released in the same geographical region as WC1 smolts, Kristiansen *et al.* (2000) estimated that 50 percent of recaptured tags were not reported by fishers. A further factor is that released cultured fish that stray normally enter rivers so late in the season that the sports fishery is closed in most rivers. Thus, the probability of receiving tags from these fish may be low. When all factors are taken into account, a doubling of the reported recaptures may be a fair approximation for estimating total returns (Hansen 1981, Hansen 1986, Isakson and Bergman 1978). In the following paragraphs reported tag recoveries are presented, except for the data shown in Figure 18.

Different proportions of the released smolt groups were tagged with Carlin tags; between 8 and 30 percent of the fish in WC1 and WC2 and from 50 to 100 percent in WC3 and WC4, partly depending on the numbers released.

Release strategies

Because of differences in the aims and organisation of the projects, practical restrictions and different physical and geographical conditions at the release sites, it was necessary to develop a range of release strategies.

During smoltification and silvering the young salmon develop the ability to osmoregulate in full-strength seawater (Hoar 1976). The process is synchronised by photoperiod and partly entrained by temperature (Folmar and Dickhoff 1980). In sea ranching it is important to find the "optimal" release period, and technique during the parr-smolt transformation to maximise post-release survival, as the transfer from fresh- to seawater may be critical. In WC4 the smolts were released upstream in the river Vefsna and were thus given the opportunity to enter seawater voluntarily. The connection with freshwater was weaker in the other projects. Smolts were released not far upstream of the river mouth, directly into the estuary or transferred to net pens in the sea. Experiments on remote marine releases were also performed. Net pens were towed from the head of the river mouth, where the release site was located, to the outer region of the fjord before the smolts were released (WC3). Acclimatisation to seawater through periods in net pens in seawater prior to release was chosen in both WC1 and WC2, but in the course of the programme methods were developed to facilitate adaptation to seawater by creating artificial salinity gradients resembling a river estuary. This was done by spreading a floating 3 m deep tarpaulin across the release bay to accumulate the surface freshwater runoff in the inner part of the bay in WC1 (Skilbrei *et al.* 1994b). Similar conditions were established in WC2 when freshwater was delivered by pipeline to net pens that were closely surrounded by a 3 m deep tarpaulin to establish a fresh-/brackish water layer, 1 to 2 m deep.

Genetic monitoring

Preservation of the genetic variation in natural stocks is important for continued evolution (Ryman, 1981). Aquaculture activities, such as stock enhancement, aquaculture and artificial breeding may have impacts on native gene pools if sea-ranched or escaped farmed salmon stray, because the hatchery environment represents new conditions which can induce drift in the gene pool. For this reason, an expert group recommended developing a research programme during the PUSH-programme to study the potential impact of sea ranching on wild stocks (Mork, 1989). Ten years later there is still little information that documents the genetic structure of salmon populations in Norway. Jørstad *et al.* (1999) offers an overview and evaluation of the genetic aspect of the PUSH programme.

Studies of genetic variation in a wild stock were only performed as part of project WC1. The main focus was on quantitative traits. Family groups of the three stocks from which the brood fish were collected and compared with respect to factors as growth rates, smolt sizes, size at maturity and return rates. During the programme substantial genetic differentiation was observed between the stocks for the allelic frequencies of six polymorphic enzymes investigated (Skilbrei and Skaala, 1997). In addition, a study was designed specifically to study the genetic and ecological consequences of immigration from a ranched to a wild population. In addition to smolts produced in WC1, smolts from the same river's stocks that possessed a genetic marker (found among the wild parents after screening for *polymorphe allozyme loci*) were transported and released in the small river River Øyre. Unfortunately, due to financial constraints and poor survival of the released fish, the gene pulse was too weak to be quantified during the programme.

The recommendations by Mork (1989) that broodstock of local or regional origin should be used were followed in all projects. Knowledge of the genetic variation in wild populations and potential genetic interactions with wild stocks is needed to perform risk assessments (Busack and Currens, 1995) and to develop sustainable ranching (Anon., 1993). The programme did not deal with this aspect. However, the fact that straying rates and the geographical distribution of the strayers differed between projects, and seemed to be influenced by rearing and release methods, offers hints as to how future sea-ranching projects should be planned.

Fish health management

After brood fish collection and fertilisation of the eggs, the eggs from each female were kept separately in a quarantine section of the hatchery while the brood fish were screened for diseases. Some groups were destroyed due to *furunculosis*. The fish were kept under veterinary control during the culture phase in freshwater, and more intensive screening for pathogens were carried out before transport and release.

EVALUATION PROGRAMME

Goals for sea ranching

The basic objectives of all four projects were to find methods of increasing our basic knowledge of sea ranching of Atlantic salmon, especially regarding practical solutions employed in producing, releasing and catching returning adult salmon. The primary goal was to identify sources of variation in survival in order to incorporate these findings into the design of the projects. While the main focus was to increase adult returns, it was also an important issue (WC3) to incorporate the biological findings in a sea-ranching model based on a recreational sports fishery that was organized in a local enterprise. The programme also aimed to compare the different models for sea ranching represented by the projects. A basic target was to minimise straying in order to reduce interaction with wild salmon populations.

Quality of smolts

Opportunities for growth during the freshwater phase differed between the projects, resulting in high proportions of two-year-old smolts (2+ smolts) in WC3 and WC4.

In WC1, more than 50 percent of the fish reached smolt size after one year, and potential 2+ smolts were not used for releases. Wide variations in freshwater growth rates resulted in different proportions of 1+ smolts and clear size differences between smolts, between family groups and between stocks (Skilbrei *et al.* 1998). The outcome of the intensive part of sea ranching in freshwater is therefore difficult to forecast, compared with commercial culture of salmon, because the offspring of wild parents have not been selected for improved performance for several generations as has been the case for the cultured Norwegian strains. For these reasons, the production of smolts for sea-ranching purposes will be more expensive than growing cultured stocks for cage rearing. In addition to physical factors determining the growth rate (as temperature), the cost of the smolts will depend on the inherited potential for freshwater growth of the stock in question, implying that the choice of stock is an important first step when planning sea-ranching projects.

The releases of unfed fry in two upper tributaries in Vefsna (WC4) resulted in yearly smolt runs that ranged from 200 to more than 4 000 individuals. Over the years, production was equivalent to 1.0 and 1.1 smolt/100 m2 in the two tributaries. It was concluded that growth rate and survival were high compared with rivers naturally populated by salmon, but that both factors are reduced if too many fry are released annually. It was supposed that the quality of these smolts is equivalent to that of wild smolts.

The quality of cultured smolts is difficult to measure. During the smoltification process the ability to osmoregulate in full-strength seawater develops. The physiological response to salinity increases and can be measured, but important questions about the behaviour of smolts after release still remain. Our understanding of the role of the rearing environment for the development of the individual is limited, especially when discussing whether, or to what extent, a cultured fish is capable of behaving naturally after being released into the wild (Svåsand *et al.*, 1998b). The smoltification process is timed by environmental cues and is believed to be crucial for survival in the sea, i.e. smolts should be released at an optimal stage of this process. In all projects, smolts were released during a period of several weeks in spring or early summer (May–July) depending on latitude. In WC1 an attempt was made to evaluate the release method by surveying the behaviour of the smolts after release by underwater video. The tendency to organize in rapidly swimming schools was taken as a measure of the preparedness of the smolts to migrate, and then it became clear that migration motivation develops gradually over several weeks as a behavioural part of complex changes associated with smolting (Skilbrei *et al.*, 1994a). In sea ranching operations too early releases may result in increased mortality. For this reason, smolts should be size-graded before release as the development of migration motivation is also size-dependent.

Adult returns

In both WC1 and WC3, the annual recapture of adults at the release site was approximately one percent of the number of smolts released, i.e. an annual recapture of 300 to 370 individuals in the Selstø Bay and 618 to 1 498 salmon in Opløy. However, a considerable fraction of the fish was recaptured in the vicinity of the release sites (see Contribution of hatchery fish to fishery). The total recapture of Carlin-tagged smolts was somewhat higher in WC1 (Table 3).

Except for a homing of 2 percent of 7 400 smolts released in 1991 into the river mouth at the WC2 release site, the catch at Vega was insignificant compared with numbers released until 1996. Following the 1995 releases 4 400 adults homed to WC2 during the next three years, equivalent to 3.3 percent of the release. The corresponding number was lower for the Carlin-tagged two-year-old smolts (2.2 percent), possibly demonstrating the combined effects of tag loss and higher mortality of tagged fish.

There are two main reasons for the evident improvement of the Vega (WC2) releases. The smolts released in 1995 homed much more successfully than previous year-classes, showing a much more pronounced geographical distribution. In addition, while one year-old smolts dominated the other release years, 97 percent of the 1995 smolts were two year-old smolts. The one year-old smolts of the Vefsna stock performed poorly in both WC2 and WC4 (Table 3). Results from WC4 indicate that such effects may be due to size differences between one and two year-old smolts.

TABLE 3. Adult recaptures as percentage of Carlin-tagged one- (1+) and two-year old smolts (2+)

Release year	WC1		WC2		WC3		WC4	
	1+	2+	1+	2+	2+	2+	2+	2+
1989	–	–	–	–	4.6	–	–	–
1990	–	–	–	–	–	3.3	–	–
1991	<0.1*	–	–	–	0.4	0.1	–	–
1992	3.6	–	0.4	2.9	2.3	1.5	–	3.2
1993	3.9	–	0.4	2.1	1.0	2.5	0.1	0.9
1994	–	–	–	–	0.1	1.5	1.2	1.5
1995	–	–	–	3.1	–	1.8	–	0.3
Total	3.8		0.7	3.0	1.6	1.8	0.5	1.2

*VI–tagged smolts, not included in total.

In general, there was high degree of variability in survival rates operating at various levels; between families, stocks, release sites, age classes, release methods and years. Whereas specific groups showed survival close to 0 percent, the highest scoring groups of WC1, WC2, WC3 and WC4 produced 12.8, 6.4, 5.0 and 3.4 percent tag recoveries, respectively. The genetic origin of the fish was one of the factors that contributed to variations in return rates (Skilbrei and Skaala, 1997), as has also been shown in Icelandic experiments at family level (Jonasson *et al.*, 1997).

In WC1 and WC2, where low freshwater discharges presented potential problems for smolt transfer to seawater, the creation of salinity gradients in the net pens presumably facilitated the parr-smolt transformation by offering the fish salinity alternatives that may have resulted in higher returns and/or improved homing ability in subsequent years (from 1992 in WC1 and from 1995 in WC2). In WC3, towing the net pens to the outer part of the fjord before releasing the smolts decreased avian predation in the fjord and raised survival rates above those of the river-mouth releases (to 6.4 percent).

Information has recently become available to suggest that increased abundance of salmon lice, possibly due to cage rearing of salmon, may reduce the survival of wild salmon. Coincident with the rapid growth of cage rearing in the region where WC1 was located, the size of local wild stocks in this area have declined drastically during the past decade. Studies on migrating wild smolts have shown lethal salmon lice infestation rates on the Norwegian coast (P. Jakobsen, University of Bergen; B. Finstad, Norwegian Institute for Nature Research, personal communication). Very high numbers of lice were also found in Selstø Bay (Skilbrei *et al.*, 1994b), suggesting that the parasite fauna ought to be investigated prior to releases.

Annual variations in return rates in the projects were presumably a consequence of factors mentioned above and large-scale fluctuations in the Norwegian Sea ecosystem. The geographical location of the release site may influence predation, smolt survival, smolt and adult navigation and the ability of the spawning migrating adults to be caught in different ways. It is impossible to fully compare the four release sites with respect to survival of smolts because of differences in release methods, stocks etc.

The effects of releasing unfed fry were measured by Carlin-tagging smolts caught in fish ladders as they were migrating out of the two upper tributaries of the River Vefsna (WC4). A mean survival to the adult stage of 0.9 percent indicates that naturally produced smolts had a return rate between those of cultured 1+ and 2+ smolts (see Table 3). Utilisation of former "unproductive" areas in the upper tributaries of salmon rivers represents an inexpensive smolt supplement that adds significantly to the natural smolt run and increases adult returns.

Interaction with natural populations

Sea ranched smolts can interact directly with natural populations if they are released into a river system that supports wild salmon, if they compete with wild salmon during the feeding period in sea and if they stray when they are entering freshwater to spawn. In addition, indirect interaction may be seen if the number of fishing gears increases in response to the releases.

River releases

Releases of juveniles into a river may represent a major energy input to an ecosystem that is mainly based upon extraneous supplies of organic matter. The consequences are poorly understood, but reduced survival of the wild juveniles may be a result, either due to increased competition and/or because of a build up of predatory stocks (Sægrov and Skilbrei, 1999). A preferable strategy may therefore be, as in WC4, either to release the fish as smolts because they are supposed to leave the river rapidly after release, or to use those tributaries for stocking of unfed fry where salmon are prevented by waterfalls, etc., from spawning.

Feeding competition

In the Pacific large-scale releases of salmonids may alter the conditions for survival and growth within and between species. In the North Atlantic, the number of salmon feeding is probably very low compared to the situation more than 100 years ago, when many large European rivers were still habitable for salmon. The yearly production of Norwegian smolts heading for the Norwegian Sea is now believed to be as low as approximately 10 million smolts. The abundance of salmon in the North Atlantic is probably far below the carrying capacity for salmon in this area, and it is not likely that the releases of smolts during the PUSH programme, 100 000-200 000 smolts yearly, have influenced this situation.

Straying

Straying was high in WC1 in comparison with assumed natural straying rates of below 10 percent. Despite the assumed rate of recaptures in rivers (approximately 50 percent of spawning run), the numbers of Carlin tags reported from rivers were comparable to or higher than the recaptures at the release site. However, the rearing environment in the hatchery tanks before release seemed to influence the straying rate. The pre-smolts held under the highest of two water current velocity regimes showed least straying, and the

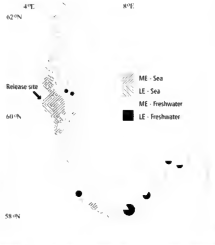


FIGURE 16. Geographical distribution of reports of ME (moderate-exercise groups kept under 1.0–2.0 body lengths/second current velocity prior to releases) and LE (low-exercise groups held in water current velocity of 0.5–1.0 body length/second) Carlin-tagged grilse released as smolts in 1992. Size of pie charts is proportional to the number of individuals, showing from one to 17 salmons. Data from Skilbrei and Holm (1998)

highest homing rate (Figure 16, Skilbrei and Holm, 1998). In the project on the outer coast, with a small watercourse (WC2), straying was low in terms of numbers but relatively high as a percentage when total returns were poor, and low (<5 percent) in 1996 when total returns were high. Releases of smolts of the same origin released in a large river (River Vefsna, WC4) gave high straying, 20–50 percent. In WC3, straying was about 4 percent every year.

In general, there was no relationship between the size of the watercourse and straying rate, or between straying and coastal and fjord/river release sites. Differences in release methods may contribute to an unknown extent to the variation in straying if it is assumed that both the handling of the smolt and their experience during this phase can influence imprinting. Nor can it be ruled out that the probability of straying may be high at specific locations due to interactions between imprinting, local hydrographical conditions, migration routes, etc.

Fishing effort

It was clearly demonstrated in WC3 that fishing effort increased in response to greater abundance of salmon in the area following releases. Over a period of five years the numbers of gill nets and bag-nets in the Opløy fjord increased by about 100 percent. In the outer part of the fjord wild salmon were more frequent in the catches than ranched salmon. Fishing pressure on wild salmon thus increases when the quantity of reared salmon increases.

Contribution of hatchery fish to fishery

For the sea-rancher the geographical distribution of the recaptures is of particular interest. If there is a commercial fishery for migrating salmon in the region, and the rancher's exclusive rights are limited to the release site, then the loss of fish may be substantial.

The fishery for adult returns in Norway can be divided into recaptures at the release site, in the commercial bag-net and gillnet fishery for migrating salmon mainly along the coast and in outer fjord regions, and fish that are taken by anglers in rivers (strayers). The reported recaptures at the release site in WC1, 2 and 3 are probably close to true recapture rates, as this fishery was partly or wholly operated by the project staff. For salmon recapture elsewhere, we have to rely principally on the number of Carlin tags reported by fishermen and anglers. These numbers must necessarily be minimum estimates.

Catch at the release site

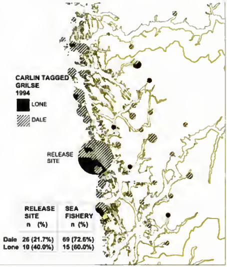
In WC1 the primary goal was to recover tags to study survival, growth rate, etc. of the released groups, and project staff therefore operated the monitoring. This was also done in WC2, which was designed to simulate a commercial sea ranching operation. Bag-nets and gillnets were utilised, with the latter proving to be most effective. One bag-net was used in WC3, but most fish were angled in the estuary of the river Opløy. In WC4 the fish were caught in the traditional sports fishery in the River Vefsna or in a fish ladder. Except in the case of WC4, there had been no fishery for salmon at the release site prior to the sea ranching programme.

Sea fishery

The contribution of hatchery fish to the sea fishery varied between release sites and year classes. It was generally high in WC1, approximately twice what was caught at the release site (example shown in Figure 16). Most of these fish were caught in the vicinity of the release site. On the basis of catch protocols provided by local fishermen, approximately 10 percent of the catches were sea-ranched salmon. However, a large but unknown percentage of their catch consisted of escaped farmed salmon. Although the number of smolts released annually was relatively low (40 000), it is likely that the releases influenced the catches of sea-run salmon in the region. The contribution to the sea fishery clearly differed between the stocks. Because of size selectivity in the fishing gears, a lower proportion of the typical grilse strain was caught in the sea fishery because they were smaller than the grilse of the other stocks (Figure 17).

In WC2, the percentage of Carlin tags reported by fishermen varied widely; from almost 100 percent in 1994 when return was

FIGURE 17. Map showing local sites of reported Carlin-tagged grilse of the Lone and Dale stocks in 1994, and a table summarizing all reported tags from these two stocks from the release site or sea-fishery. The smallest circles refer to one tag, whereas the largest circle (release site) summarizes 41 tags



	RELEASE SITE n (%)	SEA FISHERY n (%)
Dale	26 (21.7%)	69 (72.6%)
Lone	10 (40.0%)	15 (60.0%)

poor to 20 percent in 1996 when catches at the release site peaked at nearly 80 percent. In both cases, the absolute contribution of these fish to the sea fishery was low. This was also seen in project WC4, which covered the same geographical coastal zone. In WC3 – Opløy – catches at the release site were close to 50 percent of all reported Carlin tags, which was slightly higher than the number of tags recovered from the sea fishery. The majority of these were collected from the nearby Opløy Fjord.

Economic analysis (cost/benefit)

It was difficult to collect data for use in a cost/benefit analysis, partly because scientific aspects were assigned greater importance in the projects. In order to test specific hypotheses it would be necessary to keep groups of fish separate during production and release, to tag a proportion of the fish, and to monitor the catch more carefully. These operations would increase costs and reduce benefits. However, based on the experience of project WC3 – Opløy, it was possible to reach some general conclusions.

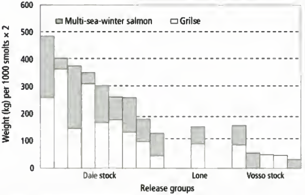
It is not possible to financially balance the operation of a sea-ranching plant through income from the sale of returned salmon. Approximately one percent of the fish returned to the release site. Calculations showed that this must rise to 13 percent before income matches costs. The economy of a sea-ranching project is improved if at least a part of the income is based on the sale of sports-fishing licences. In WC3 – Opløy income per kg fish was clearly higher for salmon that were caught by anglers than salmon caught by the project staff. A further development of this idea, not tested during the programme, would be to include fishermen who catch salmon in the sea, e.g. if the fishermen in the region pay a fee to finance the releases.

The total economy of sea ranching is obviously better than the economy of a local enterprise that raises and releases salmon on its own account, because a high proportion of the fish are caught by fishermen that do not pay their share of the costs of the releases. For these fishermen the ranched salmon supplement their catches of wild (and escaped farmed) salmon. The best-performing single release group comes close to being in balance when the economic consequences for the sea fishery are included, but the total economy of the Opløy project still are poor, dependent on which "best-case" assumptions that are made.

One reason for the poor economic results was the rapid development of the aquaculture industry in Norway during the past two decades, which has resulted in roughly a 50 percent reduction of the market price of salmon in 10 years. In addition, catches of wild salmon, i.e. survival of salmon in the sea, has been at a historically low level during the 1990s. In the present situation in Norway, it is likely that if the benefits could balance or exceed the costs of sea ranching, then the fishing licence model should be evaluated, and the release site/river ought to be chosen so that conditions are "optimal" for this approach (length of river, accommodation, distance to airports, cities, etc.)

The benefit may also be measured in terms of the quantity of food produced. Estimates of the total yield in kilograms of adults per 1 000 smolt released in WC1 show that the outcome varies substantially between stocks and family groups, roughly between 50–500 kg per 1 000 smolt released (Figure 18). When the fact that the mean smolt weight was approximately 50 g is taken into account, the total catch of the poorest surviving group is roughly equivalent to the weight of the smolts released. For the best group the weight is increased 10 times from release to recapture, demonstrating a genetic potential for optimisation. However, based on the present

FIGURE 18. Estimated total weight (kg) of returning adults per 1000 released smolts in WC1 in 1993. Numbers are multiplied by two to account for tag loss, tag mortality and non-reported tags (see **Methods of tagging** for explanation). The results for grilse and multi-sea-winter salmon are shown separately for the three stocks and two of them are further subdivided into family groups

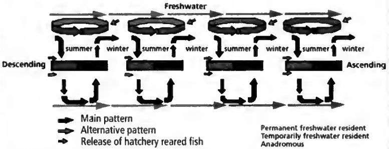


production cost of cultured smolts of US$1, and a price per kg of cultured salmon of US$3 and of wild salmon of roughly US$5, then the total catch would have to exceed 200 or 330 kg per 1 000 smolt to balance the budget, before the extra costs of release and recapture are included. If 50 percent or less of the adults are caught at the release site, then the income will be too low. This exemplifies the conclusions above. The benefits would have to be increased substantially by organizing a recreational fishery if sea ranching is to be profitable.

Associated management strategies

Due to the low natural survival rates of wild salmon since the late 1980s and the existence of high numbers of escaped farmed salmon, many native Norwegian stocks are endangered. Genetic screening of a few of more than 500 salmon stocks in Norway has shown significant genetic differences. Wild salmon stocks represent genetic resources that may be lost if not protected. The precautionary approach implies that large-scale releases of hatchery-reared smolts should be carried out with caution. High rates of straying of released smolts are of most concern. On the basis of experience gained during the PUSH programme it is clear that straying rates and geographical patterns of straying are difficult to forecast. Before sea ranching is allowed from a specific location we recommend that these factors should be specifically studied, for example using externally tagged smolts, as long-distance as well as local straying may result. This information should be included in the description of the release site, and it may be preferable to tag a number of smolts every year as the pattern of straying may change when handling procedures and release methods do so.

FIGURE 19. Migratory patterns in anadromous, permanently freshwater resident and temporarily freshwater resident Arctic char



Arctic char *(Salvelinus alpinus)*

As its name implies, the Arctic char is an Arctic fish species with a circumpolar distribution in the northern hemisphere. Char display two main different life history patterns, freshwater resident and anadromous. A combination of these two main ecological forms may be displayed in locations with upstream access from the sea; characterised as temporarily anadromous or temporarily freshwater resident (Figure 19). Freshwater resident char are the most common form. In southern (south of 65° N in Norway) and landlocked locations (mainly lakes), char are freshwater resident and complete their entire life cycle in freshwater. Generally, freshwater resident char are about 20 cm total length, and they are often found in overcrowded and stunted populations. Anadromous char are common in northern Norway, and are especially frequent in systems where there are lakes with good upstream migrating conditions for fish from the sea. Char smoltify, but external signs of smoltification are less obvious than for other salmonids, and char is the least anadromous of the anadromous salmonid fish species. Most fish home back to their native river when they reach maturity. In Norway, the main period for sea residence is June to July. Most char remain close to their native river (<30 km) during their sea residence.

No reliable catch statistics for Arctic char are available. The first attempt to sea-ranch char was made in Halsvassdraget, North Norway in the late 1980s (Finstad and Heggberget, 1993). The smolts were produced in a salmon hatchery with the same technology as for salmon smolt rearing. The initial releases of char smolts yielded high recapture rates, 10–30 percent after one stay (two months) at sea. This recapture rate was much higher than has been observed for most other salmonids. However, because of the low rate of growth of reared smolts in the sea the increase in biomass from smolt to mature fish was low, and in most cases negative. Char need 2–5 stays at sea before they reach maturation. Therefore, figures for total survival and biomass increase after the number of sea stays necessary to produce mature fish (0.5–2 kg) was the ultimate goal of the char-ranching programme. The possibilities were related to high survival rates of char during sea residence, while the limitations and problems were linked to the low growth rates of hatchery-reared fish. At the beginning of the programme little information existed regarding the life history of char, compared for example, to what is available for Atlantic salmon, and likewise as regards cultivation or sea ranching. The main goals were to investigate the possibilities for sea-ranching char and to provide basic biological knowledge that could be of importance in the future development of sea ranching and wild stock enhancement.

METHODOLOGY OF THE SEA-RANCHING PROJECT

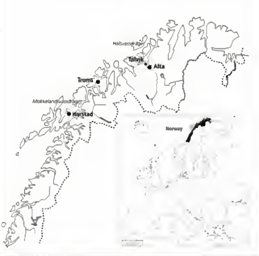
Broodstock selection

Before the programme was established it was decided that broodstock of local origin, and for the experiments in the Halsvassdraget and the Mokkelandsvassdraget (see Figure 20), native char were used as broodstock fish. In the Halsvassdraget, the majority of broodstock constituted of anadromous char, while the majority of broodstock in the Mokkelandsvassdraget constituted of freshwater resident char.

Rearing and release strategy

Char is a cold-water adapted fish species, and can easily be artificially reared by employing the same technology as for Atlantic salmon smolt production. Compared to salmon, char grow at lower water temperatures and can thus be produced with less energy demand for water heating during the winter. Char can also be kept at higher densities in the hatchery. Both one- and two-year old smolts were produced. Experiments were also carried out with releases of presmolt char and with wild freshwater resident char that had been fed for a period in the hatchery before release. The experimental fish were released in two streams, Halsvassdraget in Finnmark County, which was the main experimental stream and in Mokkelandsvassdraget in Troms County (Figure 20; Anon., 1998b). A smolt hatchery was located close to the fish trap in the River Halselva. The smolts released in the Mokkelandsvassdraget had to be transported from a hatchery in Tromsø. For the sake of comparison, both wild char caught during migration in the fish traps and hatchery-reared char were tagged.

FIGURE 20. The main distribution area of anadromous Arctic char in Norway (shown in black on the inset map). The two main experimental sites were close to Talvik (Halsvassdraget) and Harstad (Mokkelandsvassdraget)



Management of the recapture phase

As described above two main projects, including the production of release material and detailed analysis of recaptures were carried out in 1990–94 in the Halsvassdraget in Finnmark and the Mokkelandsvassdraget in Troms (Anon., 1998b). Traps were set in the streams to catch both ascending and descending fish, and the traps were sited close to the estuary of the rivers. In parts of the experiments, sub-samples of release groups of smolts were released upstream of the fish traps to analyse the migratory behaviour. Presmolt char of 8–14 cm body length were released about five to six months before smolt migration in a lake upstream of the fish trap in the Halselva. The proportion emigrating as smolts in the following spring were recorded in the fish trap.

To monitor recapture rates, individual growth and migration patterns, sufficient numbers of experimental fish were individually tagged with visible external tags. Carlin tag is the most commonly used tag for salmonids in Norway, which is easily detectable with an individual number. A reward is given to fishermen reporting tagged fish, which helps to ensure that fish captured outside the release area are also reported. In cases where information about recaptures outside the site of release is not required, simpler and less expensive tagging methods than Carlin tagging were employed. Colour tagging or finclipping were used to compare survival and growth of different groups of fish that were released. These tagging methods enabled us to compare the performance of smolts of different ages and sizes.

Genetic monitoring

No genetic monitoring was carried out.

Fish health management

The fish were reared according to the fish health regulations for Atlantic salmon in Norway. To avoid transferring disease between wild and cultured fish, the groups were kept separately in both the hatchery and fish traps. The ranching experiments were carried out during a period (1990–1994) of extremely high rates of infection of salmon lice along the Norwegian coast. This situation is now improving, mainly due to synchronised delousing in Norwegian salmon farms, but also due to extremely mild winters in the early 1990s on most of the Norwegian coast. Apart from high intensity and high prevalence of salmon lice on returning char, no other diseases were reported. The main effects of salmon lice are reduced survival and reduced growth rates during periods in the sea.

EVALUATION PROGRAMME

Sea-ranching goals

The char programme had the following main objectives:

- To establish basic knowledge relevant to the future development of sea ranching and mitigation of anadromous char stocks.
- To compare the performance (survival, growth) of different ecological groups (anadromous vs. freshwater resident) and wild vs. hatchery reared char in sea ranching.
- To analyse the possibilities with char in sea ranching and mitigation of wild stock.

Measures of success

One of the main objectives of the experiments was to compare the performance of wild and hatchery-reared char (presmolt, one- and two-year-old smolts). Studies of some basic life history patterns in anadromous char in the Halsvassdraget (Finstad and Heggberget, 1995) showed that the smolts of wild char (first-time migrants) in the Halsvassdraget varied between 13 and 27 cm body length, and individuals between 17 and 20 cm had the highest survival rates during their first stay at sea. The main period of smolt descent is between 1 June and 22 June, while most of the wild char ascended River Halselva after their first stay in the sea between 29 June and 3 August (Anon., 1998b). Overwintering adults emigrated 15 to 30 days earlier than smolts (first-time migrants), and the largest individuals descended early in May. Hatchery-reared char released as presmolts in a lake upstream of the trap, ascended later and over a longer time span than wild smolts. In both groups the largest individuals ascended earliest, while smaller and often immature individuals ascended later in the season. If the data from the recaptures of hatchery-reared char is compared to the data from the monitoring of wild char, wild char display significantly higher survival (Figure 21). The most striking differences in survival after each sea stay are seen between wild and hatchery-reared first-time migrants (smolts). Hatchery-reared smolts had survival rates of about 10 percent, while wild char (>25 cm) had survival rates of about 68 percent. In both wild and hatchery-reared char survival increased with the number of periods in the sea. This is mainly an effect of increasing size with increasing numbers of sea stays, but is also an effect of experience in older fish (Heggberget, unpublished). The highest return rates were obtained for wild char during their third stay in the sea (92 percent), which is extremely high compared to other salmonid fish species.

Wild char stayed at sea for a significantly shorter time ($p<0.001$) than hatchery-reared char, with means of 32 and 57 days respectively (Finstad and Heggberget 1995). In spite of the shorter time spent at sea, wild char displayed a significantly better rate of growth than hatchery-reared char. This is shown in Figure 22, where both survival and growth are included in calculations of biomass returned in relation to biomass descended. The results of calculations of returned biomass in relation to biomass of fish descended, (released in hatchery reared fish), are essential for calculating the economics of traditional sea ranching, since the financial return is based on fish meat sold. The results of the Halsvassdraget study clearly show that the increase in biomass is far below what is needed for traditional sea ranching with char to become financially viable.

It should be emphasised that some of the results obtained in the char programme are dependent on the methods employed and on the current situation in the sea as this affects the survival of anadromous salmonids. The results of releases of

FIGURE 21. Recapture (%) of wild and hatchery-reared Arctic char after 1–4 sea stays

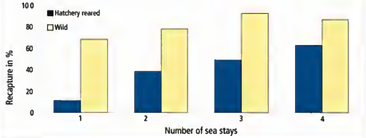
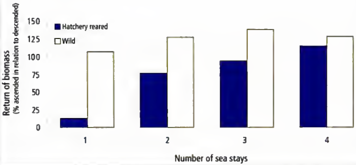
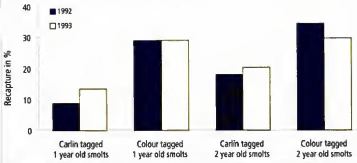


FIGURE 22. Return of biomass in wild and hatchery-reared Arctic char



hatchery-reared char smolts in 1992 and 1993 are examples of factors that affect the results of experiments with char. Tagging is necessary in experimental work because detailed information about release groups is essential. Depending on the goals of the experiments, different tagging methods were employed. The results clearly indicate that survival is affected by the method of tagging; external tags produce higher mortality than internal tags (Figure 23). It can also be seen that two-year-old smolts perform better than one-year-old smolts. This is because two-year-old smolts are larger, but is also an indication that factors connected to production procedures in the hatchery are important to the success of released fish. In a commercial operation, it is normally not necessary to tag the fish by external tags. It has frequently been shown that all extra handling of fish, such as tagging, reduces survival. Some tags will also be lost or ignored at recapture. The results presented for char based on the experimental work described here, therefore, represent absolute minimum rates of recapture. In a practical commercial operation, both survival and growth increase would be higher as a result of less handling and manipulation of the fish. It should also be mentioned that the experiments with char were carried out in a period with high infections of sea lice on char, which negatively affects both survival and growth during residence in the sea.

FIGURE 23. Recapture rate of Carlin- and colour-injected tagged 1- and 2-year old hatchery-reared smolts in 1992 and 1993 (Anon., 1998b)



Contribution of hatchery fish to fishery

During the experimental period of sea ranching char, about 100 000 smolts were released in the river Halselva alone. This contributed significantly to the fisheries, both in the sea and in freshwater. On the basis of external of tagging of some of the released fish, detailed reports on recaptures are available, showing that most recaptures were within 30 km of the site of release. The results clearly show that smolt releases are a possible means of enhancing natural stocks of anadromous char. The results also show that there is a potential for improving the performance of hatchery-reared char relative to wild char.

Economic analysis

In the economic evaluation different approaches were evaluated, as e.g. production combined with angling or "trophy" fishing (Anon., 1998b). There is a potential, but so far such activities have not yet commenced. Concerning aquaculture production of char, PUSH has performed the necessary evaluations to stimulate such activities, either as fish farming or in combinations with sea ranching. The last few annual productions of char reached 300 to 400 tonnes. An increase in the exportation rate of this species is unlikely since char is less known in middle and southern Europe. The marketing will be costly if char is to reach for instance the level of rainbow trout with 20 000 tonnes annually. Due to limited funds in push the activities had to be finalized in 1993/1994.

GENERAL CONCLUSIONS AND FUTURE PROSPECTS

Ever since humans began to harvest marine fish stocks there have been wide fluctuations in yield with respect to quantity, size and species composition. There may be several causes for this, and the blame has often been put on individual elements such as overfishing or environmental factors. During the past hundred years we have tried to enhance and rebuild fish stocks. In most cases, the goal has been to strengthen the fisheries of a specific species or stock, while we are currently experiencing a greater need to rebuild stocks threatened with extinction. As shown in this paper, stock enhancement is not straightforward, and comprises much more than merely releasing fish or crustaceans.

Main conclusions

Knowledge acquired through the PUSH research programme has provided valuable insight into factors that regulate fish production in our fjord and coastal areas. It is concluded that the economic aims for sea-ranching activities must be evaluated in a long-term perspective, and beyond the duration of the PUSH programme. It was not possible to develop commercial sea-ranching activities for any of the species concerned. However, biological and ecological requirements have been clarified.

Sea ranching of cod, salmon and char has been terminated, while promising results with lobster have led to a continuation for a few more years in order to cover more of the recapture period. We describe below in more detail the requirements for stock-enhancement or sea-ranching activities that we have reached for the four species presented in this paper.

Biological and ecological requirements

In EUROPEAN LOBSTER knowledge acquired from the large-scale hatchery run by Tiedemans at the beginning of the 1980s formed the basis of the stock-enhancement programme. For technical reasons, the environmental conditions in the hatchery were not as stable as could have been desired. Survival from hatching to settlement varied from year to year from 3.1 to 4.6. The tagging technique employed proved to be reliable, and juveniles as small as 8 to 10 mm carapace length could be tagged. From 1990 to 1994 about 170 000 juveniles were produced and about 128 000 of these were released at Kvitsøy in southwestern Norway. Some releases were also made in other areas, but due to financial constraints they could not be followed up. It is concluded that it is possible to increase the total population in an area by releasing cultured juveniles. It was also shown that cultured lobsters do not replace wild lobster, but represent an addition to the stock. An important task in relation to the release experiments has been to increase our knowledge of basic population dynamics parameters such as mortality, growth, recruitment and maturation. In this respect is has been shown that with a minimum legal size of 25 cm total length (introduced on 1st October 1992) all females have spawned once before capture and a majority also twice. No cultured lobsters have been found outside the release area, and preliminary results also show very little local migration. The majority were stationary, but few specimens have travelled distances of 2–3 km. Furthermore, genetic studies have demonstrated that genetic changes are also likely to occur when lobsters are cultured, ant it is therefore important to carefully evaluate number of lobster used as broodstock (genetic drift) and differences between wild and farmed environments (selection).

For **ATLANTIC COD**, one of the prerequisites of the release experiments was to develop several production units in different coastal and fjord areas. Cod juveniles were produced either in seawater enclosures, plastic bags, large containers or small indoor tanks. There were varying results in all the systems, but a total of 1.2 million cod juveniles was produced, where of 720 000 were tagged and released in various coastal and fjord locations, providing important information on migration, survival, growth and recapture. Various release strategies were tested, including training juveniles to develop normal anti-predator behaviour. Recapture rates ranged from 0 to 30 percent depending on area, time and size at release. In most of the release areas, a positive correlation between the size at release and survival was observed. Individual growth was highest in the outer coastal areas. The results also showed a slower rate of growth in northern fjord areas than in corresponding southern areas. Ecosystem analyses were performed for the most important release areas in Hordaland and Troms, and large differences were found in carrying capacity, and growth and survival rates.

The unique knowledge obtained, will be important both for the further development of stock enhancement in Norway and also as a basis for evaluation of stock with marine species in other countries.

In **ATLANTIC SALMON** the production of smolts is well understood from intensive aquaculture, and was found suitable for sea-ranching purposes as well. In the release experiments emphasis was placed on studying variation between large and small watercourses, releases directly in the ocean, time at release, release methods and comparisons of the performance of different stocks. A great deal of background information relevant to the evaluation of smolt quality and suitable release methods has thus been obtained. A total of 1.2 million smolts were released. No systematic differences in recapture rate or straying could be found between releases made in watercourses close to the coast and those further out in the fjord system, but the geographical straying pattern varied between the specific release sites. In general, mean yearly recaptures were low, ranging from 0.5 to 3.8 percent. However, there was a high degree of variation between release groups; from close to 0 to 12.8 percent total tag recovery. These differences, which seemed to be related to the treatment and origin of the released fish, probably indicates a potential for further optimisation of the methods of salmon sea ranching. The fishing effort for salmon increased in areas with returning ranched salmon, and the proportion of wild salmon in the catches increased with distance from the release site. Cultured salmon should therefore, in principle, be harvested at or close to the location of the release. Egg batches were kept in quarantine until the brood fish had been screened for diseases, and no diseases were detected prior to releases. The negative interaction between wild and sea ranched salmon of most concern was the high straying following many of the releases. Cost/benefit analysis gave negative results, partly because of too low returns and because 50 percent or more of the adult salmon was caught outside the release area. The highest income was seen when the fishery at the release site was organized as a sport fishery. There may be a need to include the sea fishery in a region in a sea ranching model in which the costs of the releases are shared. One alternative, also investigated, was to release yolk sac fry in the upper tributaries of a river. This method resulted in a non-expensive smolt production of at least one individual/100 m^2 .

Research on **ARCTIC CHAR** provided valuable information regarding the production of smolt relative to intensive cultivation. The projects focused on factors that influence the quality of the cultured smolts, and suggested that a combination of light, temperature and feed concentration was of importance. The use of wild char smolt as an alternative to commercially produced smolt was studied, but even though releasing wild char reduced the costs per smolt, factors such as variations in age, maturity and parasite attacks became a problem. Char spend much shorter periods, approximately 30 to 50 days at a time, in the ocean than salmon. Char is a northern circumpolar species with several ecological forms, and the seaward migration pattern is probably an adaptation to extreme climatic conditions with large seasonal changes. It is therefore reasonable to assume that feeding migrations take place because food is more readily available in the oceans than in lakes or river systems. About 123 000 individuals were released. In comparison with other salmonid species the recapture percentages were high, but somewhat variable. While only 10 to 30 percent of the first-time seaward migrants survived the ocean period, the return varied from 70 to 90 percent for larger fish (veterans). The proportion of char that made a seaward migration (the anadromous part) varied from river to river. It is uncertain whether there is a genetic difference between stationary and anadromous char in the river systems. The bottleneck in sea-ranching char is the high mortality suffered by first-time seaward migrants. Fish below 20 cm total length suffered a mortality of over 90 percent during the ocean phase. Char spend most of the ocean period close to the shore in areas with such fish species as cod, and a high degree of predation can thus be expected.

Sufficient knowledge is now available to cultivate char where wild stocks have been reduced or destroyed. It has also been shown that hatchery-reared char can contribute significantly to the fisheries, both at sea and in freshwater. The potential for char ranching is related to the combination a commercial fishery with the development of a sports fishery for returning fish. The quality of hatchery-reared char can be improved by further experiments on rearing technology. Hatchery char smolt production is only about 10 years old, while hatchery salmon smolt production has been going on for about 50 years. Thus, increased experience of smolt production and improvements in release techniques will certainly improve the results of char ranching.

Juridical requirements

Stock enhancement and sea ranching are fields or disciplines that requires different legal approaches and efforts. In a depleted stock, the fishing pressure is already heavy and will most likely increase further as a result of the releases itself. This has, among others, been observed in the enhancement project with lobster. In this respect, the increase in the total stock will be of a short-term character. A sustainable strategy aiming to restore a stock to previous recruitment levels must include new approaches in management. Ideally fishing activities should cease for a period of time, but such actions are usually very difficult, not say impossible, to introduce.

On the other hand, before a commercial sea-ranching industry can be established, legislation that ensures the right to recapture the released animals will have to be developed and introduced. A proposal for a new law for sea ranching was prepared during the programme, as Norway had no legislation concerning sea ranching. This means that neither private nor public institutions can claim ownership of released organisms, though there may be exceptions when these are marked or tagged. The development of a sea-ranching industry requires thorough examination of the legislation, and it was necessary to draw up an Act on sea ranching. A special legislation group was appointed to carry out this task and its recommendations were made in 1994 (Anon., 1994). The committee suggested a law of exclusive rights for releases based on applications and concessions assigned by relevant public authorities. Unlike "general rights" ("commons": the legal right of access to private land) to fish, assigned rights would secure exclusiveness. The report was later sent out for public reactions. The Ministry of Fisheries evaluated the recommendation in 1996. In autumn 1999 the final law proposal was sent out for reactions and evaluations, and was submitted to Parliament in the spring 2 000 session. The new *Act on Sea Ranching* will only deal with molluscs, crustaceans and echinoderms. Fish are not covered, mainly in order to reduce possible conflicts of interest. The new Act will ensure an exclusive harvesting right for the owner of the permission to release.

Economical requirements

Economic evaluations of the release projects were considered important, and profitability analyses were made, both with respect to the possible development of private enterprises as well as to the evaluation of socio-economic aspects. In general, survival rates in the sea were too low to make sea-ranching activity profitable, and the market price for cod, salmon and char would have to double or triple to make commercialisation worthwhile. However, reducing costs per animal released as well as including steps to improve survival and growth are possible approaches that can improve the prospects of profitability. Not even with lobster does appear that there are any private enterprise developments in the short run, although enhancement seems to have the potential to become socio-economically viable. In this respect, offspring or second-generation organisms must be taken into consideration and it is assumed that the effective or total production will increase as a result of the releases.

Strengths

The strength of the programme was that the entire range of Norwegian expertise was involved. Adequate budgets were provided to enable the projects to obtain the knowledge needed to answer the question of whether ranching of the species concerned could become financially viable. This created a platform for future collaboration between scientists from different organizations and institutions in

Norway. Collaboration between disciplines such as biology, economics, social sciences and technology were developed through the PUSH programme and were shown to be important in later research activities, both in Norway and elsewhere.

Weaknesses

One may ask whether the objective of PUSH, "profitable industry", was capable of being achieved before biological and economic requirements were known. The board of the PUSH programme emphasised that patience had to be shown regarding goals related to employment and industry. As early as 1992–93 it was pointed out that the financial goals for sea ranching would have to be evaluated in a long-term perspective, and beyond the duration of the PUSH programme. This conclusion has not changed.

The programme period was too short to repeat important experiments because the life cycles of some of the species involved are of the same length as the duration of the programme. The releases of salmon and char were carried out during a period with low "natural" survival caused by a negative marine productivity cycle and high infection rates of sea lice. To some extent the management of the programme was too politically driven, and it became more important to release large numbers of organisms than to carry out experiments according to scientifically accepted methods. It would probably have increased the chances of success if fewer fish had been released, the number of release sites increased and the monitoring period extended. This would have improved the chances of identifying suitable release locations for sea ranching in Norway. A better way of reaching the goals of the programme would therefore have been to carry out more scientific experiments designed from the general lack of knowledge relevant to sea ranching, than to release high numbers of organisms in a few locations from the point of "profitability".

Evaluation of other fishery management options

It is an interesting question whether regulating the ordinary fishery more strictly for a period can be a more cost-effective strategy for increasing stocks than accepting the costs of producing juveniles for release purposes. Such analyses did not form a part of the programme when it started, nor were such analyses given much attention in the course of the programme. One reason for this is that it is not easy to evaluate the effects of different fishery management options. Some concern was expressed about Atlantic cod and lobster stock management at the symposium arranged by PUSH in September 1997 (increase in minimum size).

The Board of Push produced a synopsis of stock-enhancement projects in other countries on the basis of several study trips. In the western United States salmon resources are controlled by means of various techniques, and declining yields are believed to result in part from shortcomings in the regulatory process. Spawning refuges, habitat protection and restoration, and the construction of fish reefs are such examples.

Prospects and lessons for future programme

Several lessons can be drawn from the PUSH programme, but among the most important is that to manipulate marine ecosystems is extremely difficult owing to the many feedback mechanisms, such as density-dependent growth, mortality, etc. Furthermore, all background information must be thoroughly evaluated before commencing a stocking programme. One should not maintain unrealistic expectations regarding the development of commercial activities in a short time frame, as also strongly emphasized by Hilborn (1998). The development of commercial activity requires there is a solid biological and ecological basis for increased yield. This can only be ascertained if we know the scientific basis, in which case the commercial prospects can be evaluated and assessed via ordinary economic models.

Optimal collaboration between associated disciplines such as ecology, economics, technology, social sciences and the fishing industry will be required in the development of alternative sea-ranching activities in the future. It is also essential to recognize that developing economically and ecologically sustainable techniques of sea ranching with different species will take some time from the first attempts to practical operation. Patience will therefore be necessary in future work if we are to develop a new industry based on sea ranching.

References

Addison, J.T. & Bannister, R.C.A. 1994. Re-stocking and enhancement of clawed lobster stocks: a review. *Crustaceana* 67(2): 131-155.

Agnalt, A.-L., van der Meeren, G.I., Jørstad, K.E., Næss, H., Farestveit, E., Nøstvold, E., Svåsand, T. Korsøen, E. & Ydstebø, L. 1999. Stock enhancement of European lobster (*Homarus gammarus*); A large-scale experiment off south-western Norway (Kvitsøy). *In* B. Howell, E. Moksness & T. Svåsand, eds. *Stock Enhancement and Sea Ranching* pp. 401-419. Oxford, Fishing News Books, Blackwell Science. 606 pp.

Agnalt, A.L. (unpubl. a) A fecundity analysis of European lobster (*Homarus gammarus*) distributed off south-western Norway, with special emphasis on differences between native and cultured lobster

Agnalt, A.L. (unpubl. b) Maturation; did the releases of European lobster juveniles (*Homarus gammarus*) impose a negative effect on the native animals?

Aiken, D.E. & Waddy, S.L. 1995. Aquaculture, pp. 153-175. *In* J.R. Factor, ed. Biology of the lobster (*Homarus americanus*). New York, Academic Press, 528 pp.

Allendorf, F.W. & Ryman, N. 1987. Genetic management of hatchery stocks. *In* N. Ryman & F. Utter, eds. *Population genetics and fishery management*, p. 14-159. Seattle, University of Wasington Press.

Anon. 1989. Plan for utvikling og stimulering av havbeite/havbruk (PUSH) (A plan to develop and stimulate sea ranching). *Innst. St. nr.*, 244:25-28. (In Norwegian).

Anon. 1990. Gjennomføring av det finanspolitiske opplegget for 1990. *St.prp. Nr.*, 95. (In Norwegian).

Anon. 1994. Lov om havbeite. *Norges Offentlige Utredninger*, NOU 1994:10. (In Norwegian).

Anon. 1995. *Yngelproduksjon av torsk. Hva har resultatene vist? Sluttrapport.* (Summary report of juvenile production of Atlantic cod (*Gadus morhua*) funded by the Norwegian Sea Ranching Programme 1990-1997). Program for utvikling og stimulering av havbeite. (In Norwegian).

Anon. 1998a. Havbeite med røye - artsrapport. (Summary report of all sea-ranching projects with Arctic char (*Salvelinus alpinus*) funded by the Norwegian Sea Ranching Programme 1990-1997). Norges Forskningsråd. (In Norwegian).

Anon. 1998b. *Havbeiteprogrammet PUSH: Styrets sluttrapport.* (Summary report of all stock-enhancement and sea- ranching projects with European lobster (*Homarus gammarus*), Atlantic cod (*Gadus morhua*), Atlantic salmon (*Salmo salar*), and Arctic char (*Salvelinus alpinus*) funded by the Norwegian Sea Ranching Programme 1990-1997.) Norges Forskningsråd. (In Norwegian).

Anon. 1999. Havets Ressurser. *In* R. Thoresen, ed. *Fisken Hav*, Suppl. 1. 153 pp. (In Norwegian with English abstract).

Appelöf, A. 1909. *Undersøkelser over hummeren (Homarus vulgaris) med særskilt hensyn til dens optræden ved Norges kyster* (Investigations of lobster [*Homarus vulgaris*] with special emphasis on its behavior on the Norwegian coast). Efter foranstaltning av Stavanger filial av selskapet for de Norske fiskeriers fremme. Bergen, A.S. Johns Griegs Boktrykkeri. 154 pp., 10 illustrations.

Bannister, R.C.A., Addison J.T. & Lovewell, S.R.J. 1994. Growth, movement, recapture rate and survival of hatchery-reared lobsters (*Homarus gammarus* (Linnaeus 1758)) released into the wild on the English east coast. *Crustaceana*, 67: 156-172.

Bannister, R.C.A. & Addison, J.T. 1998. Enhancing lobster stocks: A review of recent European methods, results and future prospects. *Bull. Mar. Sci.*, 62(2): 369-387.

Bennet, D.B. & Edwards, E. 1981. Should we ban the berried lobsters? *ICES C.M.* 1981/K:11, 8 pp.

Berg, E., Eriksen, I.A. & Eliassen, J.E. 1998. *Catch-statistics for Norwegian coastal cod 1984-1997 – Data and methods.* Norwegian Institute of Fishery and Aquaculture Ltd. Report 10/1998. Mimeo.

Bergstad, O.A., Jørgensen, T. & Dragesund, O. 1987. Life history and ecology of the gadoid resources of the Barents Sea. *Fish. Res.*, 5: 119-161.

Boeck, S. 1869. *Om det norske hummerfiske og dets historie* (The Norwegian lobster fishery and its history). Tidsskrift Fiskeri, utgivet af H.O. Fiedler og Arthur Feddersen, 3 Aarg. Kjøbenhavn 1869 (in Norwegian).

Borthen, J., Agnalt, A.-L., Nøstvold, E. & Sorensen, J. 1998. *Artsrapport hummer.* (Summary report of all stock-enhancement projects with European lobster (*Homarus gammarus*) funded by the Norwegian Sea Ranching Programme 1990-1997). Program for utvikling og stimulering av havbeite, NFR, 59 pp.

Borthen, J., Agnalt, A.-L. & van der Meeren, G.I. 1999. A bio-economical evaluation of a stock-enhancement project of European lobster; The simulation model LOBST.ECO with some preliminary results. *In* B. Howell, E. Moksness & T. Svåsand, eds. *Stock Enhancement and sea ranching.* pp. 583-596. Oxford, Fishing News Books, Blackwell Science. 606 pp.

Browne, R. & Mercer, J.P. 1998. The European clawed lobster (*Homarus gammarus*): stock enhancement in the Republic of Ireland. *In* L. Gendron, ed. *Proceedings of a workshop on lobster stock enhancement held in the Magdalen Islands (Quebec) from October 29 to 31, 1997.* pp. 33-41. Can. *Ind. Rep. Fish. Aquat. Sci.*, 244: 135 pp.

Burton, C. 1992. Techniques of lobster stock enhancement. *Seafish Rep. 396*, Sea Fish Industry Authority, Marine Farming Unit, pp.1-35.

Burton, C., Bannister, R.C.A., Addison, J.T. & Cook, W. 1994. Lobster stock enhancement experiments II: Current experiments in the British Isles. ICES Workshop to evaluate the potential for stock enhancement. Charlottenlund, Denmark, 19-24 May 1994. *ICES CM* 1994/F:9, p. 41-53.

Busack, C.A. & Currens, K.P. 1995. Genetic risks and hazards in hatchery operations: Fundamental concepts and issues. *Am. Fish. Soc. Symp.*, 15: 71-80.

Cook, W. 1995. *A lobster stock enhancement experiment in Cardigan Bay.* Final report. North Western and North Wales Sea Fisheries Committee, Lancaster, 33 pp.

Cover, J.M. 1996. *Introduction to system dynamics (Powersim® 2.5).* Powersim Corporation, Colorcraft of Virginia, Sterling, Virginia. 44 pp.

Cowx, I.G. 1994. Stocking strategies. *Fish. Manag. Ecol.*, 1: 15-30.

Dannevig, A. 1936. Hummer og hummerkultur (Lobster and lobster culture). *Fiskeridirektoratets Skrifter, Serie HavUndersøkelser,* Vol IV, No 12: 60 pp. (In Norwegian).

Dow, R.L. 1980. The clawed lobster fisheries. *In* J.S. Cobb & B.F. Phillips eds. *The biology and management of lobsters, Volume 2, Ecology and management.* 265-271 pp. Academic Press, New York. 390 pp.

Edwards, D.J. 1987. *Salmon and trout farming in Norway.* Farnham, Fishing News Books, 95 pp.

FAO 1981-1996. *Yearbooks of fisheries statistics, catches and landings.* Volume 50, 52, 54, 56, 58, 72, 78. Rome, Italy.

FAO 1993. *Report of expert consultation on utilisation and conservation of aquatic genetic resources.* FAO Fisheries Report 491 (FIRI/R49), Rome, Italy.

Finstad, B. & Heggberget, T.G. 1993. Migration, growth and survival of wild and hatchery-reared anadromous Arctic charr (*Salvelinus alpinus*) in Finnmark, northern Norway. *J. Fish. Biol.*, 53: 303-312.

Finstad, B. & Heggberget, T.G. 1995. Seawater tolerance, migration, growth and recapture rates of wild and hatchery-reared Arctic char (*Salvelinus alpinus* (L.)). *In* A. Klemetsen, B. Jonsson, and J.M. Elliot, eds. *Proceedings of the third international charr symposium June 13-18 1994. Nord. J. Freshwat. Res.*, 71. Trodheim, Norway. 229-236.

Folmar, L.C & Dickhoff, W.W. 1980. The parr-smolt transformation (smoltification) and seawater transformation in salmonids. A review of selected literature. *Aquaculture* 21: 1234-1252.

Free, E.K., Tyler, P.A. & Addison, J.T. 1992. Lobster (*Homarus gammarus*) fecundity and maturity in England and Wales. *ICES C.M.* 1992/K: 43.

Gendron, L. (ed.) 1998. Proceedings of a workshop on lobster stock enhancement held in the Magdalen Islands (Quebec) from October 29 to 31, 1997. *Can. Ind. Rep. Fish. Aquat. Sci.*, 244: xi + 135 pp.

Grimsen, S., Jaques, R.N., Erenst, V. & Balchen, J.G. 1987. Aspects of automation in a lobster farming plant. *Modelling, Identification and Control*, 8: 61-68.

Hansen, L.P. 1981. Merking og utsetting av laksesmolt (*Salmo salar* L.) i Glomma. (Tagging and release of smolts of Atlantic salmon (*Salmo salar* L.) in the river Glomma) *Fauna* 33: 89-97. (In Norwegian).

Hansen, L.P. 1986. The data on salmon catches available for analysis in Norway. *In* D. Jenkins & W.M. Shearer, eds. *The status of Atlantic salmon in Scotland.* pp.79-83. ITE Symp. 15., Inst. Terr. Ecol. Huntingdon, Abbots Ripton, 127 pp.

Hedgecock, D., Nelson, K., Simsons, J. & Shleser, R.A. 1977. Genetic similarity of American and European species of the lobster *Homarus. Biol. Bull.*, 152: 41-50.

Hilborn, R. 1998. The economic performance of marine stock enhancement projects. *Bull. Mar. Sci.*, 62: 661-674.

Hoar, W.S. 1976. Smolt transformation; evolution, behaviour and physiology. *J. Fish. Res. Board. Can.*, 33: 1234-1252.

Holm, J.C., Svåsand, T. & Wennevik, V. 1991. *Håndbok i torskeoppdrett. Stamfiskhold og yngelproduksjon.* (Handbook in rearing cod. Management of brood stock and larval production) Havforskningsinstituttet, Senter for havbruk. 156 pp. (In Norwegian).

Isaksson, A. & Bergman, P.K. 1978. An evaluation of two tagging methods and survival rates of different age and treatment groups of hatchery-reared Atlantic salmon smolts. *J. Agr. Res. Icel.* 10(2): 74-99.

Jakobsson, J. O.S. Astthorsson, R.J.H. Beverton, B. Björnsson, N.Daan, K.T. Frank, J. Meincke, B. Rothschild, S. Sundby and S. Tilseth (eds) 1994. *Cod and climate change.* Proceedings of a symposium held in Reykjavik, 23-27 August 1993. *ICES mar. Sci. Symp.* 198, 699 pp.

Jefferts, K.B., Bergman, P.K. & Fiscus, H.F. 1963. A coded-wire identification system for macro-organisms. *Nature*, 198: 460-462.

Jonasson, J., Gjerde, B. & Gjedrem, T. 1997. Genetic parameters for return rate and body weight of sea-ranched Atlantic salmon. *Aquaculture* 154: 219-231.

Jonsson, N. & Heggberget, T. 1993. Havbeite med laks (Sea ranching with salmon). *NINA utredning* 45, 1-43. (In Norwegian)

Jørstad, K.E. & Farestveit, E. 1999. Population genetic structure of lobster (*Homarus gammarus*) in Norway and implications for enhancement and ranching operation. *Genetics in Aquaculture*, 173: 447-457.

Jørstad, K.E., Skaala, Ø. & Nævdal, G. 1999. Genetic diversity and the Norwegian Sea ranching programme: An evaluation. In: B.R. Howell, E. Moksness & T. Svåsand, eds. Stock Enhancement and Sea Ranching pp. 49-62. Oxford, Fishing News Books, Blackwell Science Ltd. 606 pp.

Jørstad, K.E., Paulsen, O.I., Nævdal, G. & Thorkildsen, S. 1994. Genetic studies of cod (*Gadus morhua* L.) in Masfjorden, western Norway: Comparisons between the local stock and released artificially reared cod. *Aquacult. Fish. Manag.*, 25 (Suppl. 1): 77-91.

Jørstad, K.E., Nøstvold, E., Kristiansen, T. & Agnalt, A.-L. (2000) High survival and growth of European lobster (*Homarus gammarus*) juveniles in communal rearing systems with natural bottom substrate. *Mar. Freshwater Res.*, 52: 1431-1438.

Kirk, R. 1987. *A history of marine fish culture in Europe and North America*. The Dorset Press, Dorchester, 192 pp.

Koeller, P. 1998. Influence of temperature and effort on lobster catches at different temporal and spatial scales and the implications for stock assessments. *Fish. Bull.*, 97: 62-70.

Korsøen, E. 1994. *Overlevelse, vekst og klomorfologi, relatert til antall klør ved metamorfose og bunnforhold hos juvenile hummer* (*Homarus gammarus* L.). (Survival, growth and claw morphology related to number of scissor claws formed and bottom conditions in juvenile lobster (*Homarus gammarus* L.). Thesis for Master of Science, University of Bergen, 65 pp. (In Norwegian).

Kristiansen, T.S., Jørstad, K.E., Otterå, H., Paulsen, O.I. & Svåsand, T. 1997. Estimates of larval survival of cod (*Gadus morhua* L.) by releases of genetically marked yolk-sac larvae. *J. Fish Biol.*, 51 (Suppl. A): 264-283.

Kristiansen, T.S., Otterå, H. and Svåsand, T. (2000) Size-dependent mortality of juvenile Atlantic cod, estimated from recaptures of released reared cod and tagged wild cod. *Journal of Fish Biology*, 56: 687-712.

Latrouite, D. 1998. *The French experience with enhancement of European lobster Homarus gammarus*. *In* L. Gendron, ed. Proceedings of a workshop on lobster stock enhancement held in the Magdalen Islands (Quebec) from October 29 to 31, 1997. Can. *Ind. Rep. Fish. Aquat. Sci.*, 244: 55-58. 135 pp.

Latrouite, D. & Lorec, J. 1991. L'expérience française de forçage du recrutement du homard européen (*Homarus gammarus*): résultats préliminaires. *ICES mar. Sci. Symp.*, 192: 93-98.

Laurec, A. 1999. Can the conditions for a successful enhancement or sea ranching be defined? *In* B.R. Howell, E. Moksness & T. Svåsand, eds. Stock enhancement and sea ranching. pp. 1-5. Oxford, Fishing News Books, Blackwell Science Ltd. 606 pp.

Leber, K.M. 1999. Rationale for and experimental approach to stock enhancement., chapter 5. *In* B. Howell, E. Moksness & T. Svåsand, eds. *Stock Enhancement and sea ranching*, pp. 63-75. Oxford, Fishing News Books, Blackwell Science. 606 pp.

Moksness, E. & Støle, R. 1997. Larviculture of marine fish for sea ranching purposes: is it profitable? *Aquaculture*, 155: 341-353.

Moksness, E., Støle, R. & van der Meeren, G.I. 1998. Profitability analysis of sea ranching with Atlantic salmon (*Salmo salar*), Arctic charr (*Salvelinus alpinus*), and European lobster (*Homarus gammarus*) in Norway. *Bull. Mar. Sci.*, 62(2): 689-699.

Mork, J. 1989. (chairman). *Havbeite med anadrom laksefisk i Norge*. Innstilling fra forskergruppe nedsatt av Miljøverndepartementet og Fiskeridepartementet. Trondheim, Norway. (In Norwegian).

Otterå, H., Kristiansen, T.S. & Svåsand, T. 1998. Evaluation of anchor tags used in sea-ranching experiments with Atlantic cod (*Gadus morhua* L.). *Fish. Res.*, 35: 235-244.

Otterå, H., Kristiansen, T.S., Svåsand, T., Nordeide, J.T., Nævdal, G., Borge, A. & Pedersen, J.P. 1999. Enhancement studies of Atlantic cod (*Gadus morhua* L.) in an exposed area in western Norway. *In* B.R. Howell, E. Moksness & T. Svåsand, eds. *Stock enhancement and sea ranching*. pp. 257-276. Oxford, Fishing News Books, Blackwell Science Ltd. 606 pp.

Ryman, N. 1981. (ed.) Fish Gene Pools. *Ecol. Bull.*, 34. Stockholm.

Sars, G.O. 1879. Indberetniger til Departementet for det Indre fra Dr G.O. Sars om de af ham i aarene 1864-1878 anstillede undersøgelser angaaende saltvandsfiskerierne. *Christiania* 1879. (In Norwegian).

Shelbourne, J.E. 1964. The artificial propagation of marine fish. *Advances in Marine Biology*, 2: 1-83.

Skilbrei, O.T., Holm, M., Jørstad, K. & Handeland, S.O. 1994a. Migration motivation of cultured Atlantic salmon, *Salmo salar* L., smolts in relation to size, time of release and acclimatization period. *Aquacult. Fish. Manag.*, 25: 65-77.

Skilbrei, O.T., Jørstad, K., Holm, M., Farestveit, E., Grimnes, A. & Aardal, L. 1994b. A new release system for coastal ranching of salmon and behavioural patterns of released smolts. *Nord. J. Freshw. Res.*, 69: 84-94.

Skilbrei, O.T. & Skaala, Ø. 1997. A comparison between three Atlantic salmon river stocks; using classical population genetics, differences in life history traits and performance in sea ranching. *ICES. CM*, 1997/P:13.

Skilbrei, O.T. & Holm, M. 1998. Effects of long-term exercise on survival, homing and straying of released Atlantic salmon (*Salmo salar*) smolts. *J. Fish. Biol.*, 52: 1083-1086.

Skilbrei, O.T., Johnsen, B.O., Heggberget, T., Krokan, P., Aarset, B., Sagen, T. & Holm, M. 1998. *Havbeite med laks - artsrapport*. (Summary report of all sea-ranching projects with Atlantic salmon (*Salmo salar*) funded by the Norwegian Sea Ranching Programme 1990-1997). Norges Forskningsråd. 72 pp. (In Norwegian).

Solemdal, P., Dahl, E., Danielssen, D.S. & Moksness, E. 1984. The cod hatchery in Flødevigen - background and realities. *In* E. Dahl, E.S. Danielssen, E. Moksness & P. Solemdal, eds. *The propagation of cod (Gadus morhua L.)*. Flødevigen rapportserie. pp. 17-45.

Svåsand, T. & Kristiansen, T.S. 1990. Enhancement studies of coastal cod in western Norway. Part II. Migration of reared coastal cod. *J. Cons. Int. Explor. Mer.*, 47: 13-22.

Svåsand, T. 1998. Enhancement studies in Norway – Background and results with emphasis on releases in the period 1983-1990. *Bull. Mar. Sci.*, 62: 313-324.

Svåsand, T., Kristiansen, T.S., Pedersen, T., Salvanes, A.G.V., Engelsen, R. & Nodtvedt, M. 1998a. *Havbeite med torsk – artsrapport.* Norges forskningsråd. (Summary report of all sea-ranching projects with Atlantic cod (*Gadus morhua*) funded by the Norwegian Sea Ranching Programme 1990-1997). (In Norwegian with English abstract).

Svåsand, T., Skilbrei, O.T., van der Meeren, G.I. & Holm, M. 1998b. Review of morphological and behavioural differences between reared and wild individuals: Implications for sea ranching of Atlantic salmon (*Salmo salar* L.), Atlantic cod (*Gadus morhua* L.), and European lobster (*Homarus gammarus* L.). *Fish. Manag. Ecol.*, 5: 1-18.

Svåsand, T., Jørstad, K.E., Otterå, H. & Kjesbu, O.S. 1996. Differences in growth performance between Arcto-Norwegian and Norwegian coastal cod reared under identical conditions. *Fish. Biol.*, 49: 108-119.

Svåsand, T., Kristiansen, T.S., Pedersen, T., Salvanes, A.G.V., Engelsen, R., Nævdal, G. and Nødtvedt, M. (2000) Enhancement of cod stocks. *Fish and Fisheries*, 1: 173-205.

Sægrov, H. & Skilbrei, O.T. 1999. Can stocking programmes affect the predator stocks and decrease the survival of the wild Atlantic salmon juveniles? *In* B.R. Howell, E. Moksness & T. Svåsand, eds. *Stock Enhancement and sea ranching.* pp. 182-188. Oxford, Fishing News Books, Blackwell Science Ltd. 606 pp.

Sømme, J.D. 1941. *Ørretboka: ørretfiske, ferskvannsfiske, fiskekultur.* (The book about trout, fisheries and culture). Jacob Dybvads Forlag, Oslo, 591 pp. (In Norwegian).

Tracy, M.L., Nelson, K., Hedgecock, D., Shleser, R.A. & Pressick, M.L. 1975. Biochemical genetics of lobster: genetic variation and the structure of American lobster (*Homarus americanus*) populations. *J. Fish. Res. Board Can.*, 32: 2091-2101.

Tveite, S. 1971. Fluctuations in year-class strength of cod and pollack in southeastern Norwegian coastal waters during 1920-1969. *Fisk Dir. Skr. Serie Hav Unders.*, 16: 65-76.

Tveite, S. 1991. Hummerbestanden i Norge med særlig vekt på Skagerrak (Lobster stocks in Norway with special emphasis on the Skagerrak area). *Flødevigen Meldinger.* No. 4/1991/HFF, 12 pp. (In Norwegian).

Tveite, S. & Grimsen, S. 1995. Survival of one-year-old artificially raised lobsters (*Homarus gammarus*) released in southern Norway. *ICES mar. Sci. Symp.*, 199: 73-77.

Uglem, I. & Grimsen, S. 1995. Tag retention and survival of lobster juveniles (*Homarus gammarus* L.) marked with coded wire tags. *Aquacult. Res.*, 26: 837-841.

Uglem, I., Holm, M., Svåsand, T. & Korsoen, E. 1995. *Yngelproduksjon av hummer - Sluttrapport* (Production of lobster larvae - Final report). Program for Utvikling og Stimulering av Havbeite, NFR. 30 pp. (In Norwegian).

Waddy, S.L. & Aiken, D.E. 1998. Lobster (*Homarus americanus*) culture and resource enhancement: the Canadian experience. *In* L. Gendron, ed. Proceedings of a workshop on lobster stock enhancement held in the Magdalen Islands (Québec) from October 29 to 31, 1997. *Can. Ind. Rep. Fish. Aquat. Sci.* 244: 9-18. 135 pp.

Wickins, J.F., Beard, T.W. & Jones, E. 1986. Microtagging cultured lobsters (*Homarus gammarus* L.) for stock enhancement trials. *Aquaculture. Fish. Management*, 17: 259-265.

Stock enhancement of barramundi in Australia

D.J. Russell and M.A. Rimmer
Northern Fisheries Centre
Queensland Department of Primary Industries
PO Box 5396, Cairns, Queensland, 4870, Australia

INTRODUCTION

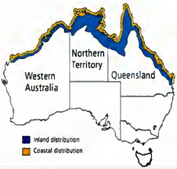
Barramundi, Lates calcarifer (Bloch) is a large, catadromous, euryhaline member of the family Centropomidae (Greenwood, 1976). Barramundi, or sea bass as it is known in south-east Asia, is widely distributed throughout the tropical Indo-west Pacific from the Arabian Gulf through Asia to Taiwan Province of China, the Indonesian archipelago, Papua New Guinea and northern Australia. In Australia, its distribution is pantropical from the Ashburton River in Western Australia to southeastern Queensland (see Figure 1; Kailola *et al.*, 1993). It is a popular recreational, commercial and aquaculture species throughout its range (Kailola *et al.*, 1993).

Life history and reproductive biology

The life history and reproductive biology of barramundi is complex and has major ramifications for the management of the fishery. In Papua New Guinea, Moore (1979) first identified barramundi as a protandrous hermaphrodite and this was later confirmed for stocks in northern Australia (Davis, 1982, 1984b; Russell, 1986). Males mature at about four years of age (Moore, 1979) and sex inversion normally occurs when the fish are about seven years old (Moore, 1979; Reynolds and Moore, 1982; Davis, 1982, 1984a). Male barramundi spawn at least once before changing sex (Moore, 1980; Davis, 1984b). Primary females, which are not derived from male fish, are also evident in some barramundi populations (Moore, 1980).

Barramundi in northern Australia spawn between September and March, with latitudinal variation in spawning season, presumably in response to varying water temperatures (Dunstan, 1959; Russell and Garrett, 1983, 1985; Davis, 1985a; Garrett, 1987). In Papua New Guinea, Moore and Reynolds (1982) found that barramundi spawning activity peaked from November to January. In both Papua New Guinea (Moore, 1980, 1982) and parts of northern Australia

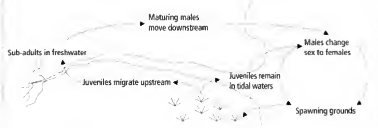
FIGURE 1. Distribution of barramundi in Australia



(Davis, 1986; Griffin, 1986, 1987; Russell and Garrett, 1985) barramundi make an extensive seaward, spawning migration from inland freshwaters to coastal waters or estuaries where the salinity is relatively high. Davis (1986) found that some fish from different river systems intermixed but found no evidence that spent fish migrated back into freshwater. Barramundi are highly fecund, with a single female (> 120 cm total length) capable of producing up to 46 million eggs (Dunstan, 1959; Moore, 1982; Davis, 1984b). High salinity appears to be an important factor in determining the location of barramundi spawning grounds (Moore, 1982; Davis, 1985a). These grounds may be located in a variety of habitats including estuaries, coastal mudflats, headlands and other nearshore waters (Moore, 1982; Davis, 1985a; Garrett, 1987).

After hatching, postlarvae enter supralittoral wetlands (Moore, 1982; Davis, 1985a; Russell and Garrett, 1985) and tidal pools and gutters near the spawning grounds where they remain for several months (Russell and Garrett, 1985). Where the opportunity exists, many juveniles subsequently move up into the freshwater reaches of coastal rivers and creeks (Russell and Garrett, 1983, 1985; Davis, 1985a). Pender and Griffin (1996) provided strong evidence that, in the Northern Territory of Australia, some barramundi do not migrate into freshwater and spend their entire life in coastal waters. Juvenile barramundi that move into freshwater habitats remain resident until they are three to four years of age (60–70 cm total length [TL]) when they reach sexual maturity as males, and then move downstream during the breeding season to participate in spawning (Davis, 1982). In Australia, there is little evidence that they return to freshwater after spawning. A generalized life cycle of the barramundi is shown in Figure 2.

FIGURE 2. Diagrammatic representation of the life cycle of barramundi


Maturing males move downstream
Males change sex to females
Sub-adults in freshwater
Juveniles migrate upstream
Juveniles remain in tidal waters
Spawning grounds

REVIEW OF FISHERY

Profile of fishery

Commercial and recreational fishing gear

Gillnets are widely used throughout northern Australia in estuaries and coastal areas to catch a range of commercial fish species including barramundi (See Plate 1). The nets are commonly made of monofilament webbing and are subject to a range of operational restrictions depending on local State or Territory regulations. Commercial fishing is restricted to tidal waters. Nets are serviced at regular intervals with fish being removed, processed (filleted or "gilled and gutted") and chilled on ice or frozen. Recreational, indigenous and commercial tour operators cannot use gillnets. They usually fish with live and dead bait and lures in both tidal and freshwaters (see Plate 2). Some indigenous fishers still use traditional fish traps to catch barramundi.

PLATE 1. A barramundi enmeshed in a gillnet

PLATE 2. Recreational fishing for barramundi is a popular sporting activity in Australia

Queensland

The barramundi is a valuable part of a multispecies commercial gillnet fishery, which is composed of almost 50 species (Russell, 1988). The gross value of production (prices paid to the fishers at the wharf) is estimated by Williams (1997) to be $A2.5 million, but when capital investment, indirect benefits and the value of the marketing sector are taken into consideration, the industry is worth considerably more. Costs of production are high, with operating expenses amounting to 60 percent of all the costs for a typical 10-m commercial fishing vessel (QFMA, 1996). In the Gulf of Carpentaria, the level of capital investment to establish a typical barramundi fishing operation is in the order of $A150 000 (QFMA, 1996) although on the east coast fishing units are typically smaller, land-based operations using dinghies (See Plate 3) Fishers may have endorsements to operate in other fisheries including the crab and trawl fisheries. Profitability at present catch rates appears to be quite low, especially for smaller units (QFMA, 1996). Environmental factors could play a role in determining the magnitude of the barramundi catch. In a study of fisheries resources of part of the east Queensland coast, Ludescher (1997) noted a correlation between increased catches and large flow events in major river systems.

PLATE 3. Processing a commercial barramundi catch

There is little available information on the recreational, indigenous and commercial tour fisheries although the Gulf of Carpentaria recreational fishery alone is estimated to have 100 000 participants per year (QFMA, 1996).

Northern Territory

The multispecies commercial inshore gillnet fishery in the Northern Territory is based on barramundi and threadfin salmon *(Polynemus sheridani)*, both of which are primarily marketed in fillet form (Fallu, 1996). Fallu (1996) estimated that the commercial value of the barramundi catch was about $A3.3 million. Commercial activity is widely distributed, but the majority of recreational activity is concentrated on the Mary and Daly rivers and streams in the Kakadu region. The recreational fishery is still developing and its value is unknown but thought to be relatively high (Fallu, 1996). There is little information on the indigenous fishery although it is known to be spread along the entire coastline.

Western Australia

Unlike the coastal areas of the Northern Territory and Queensland, the lack of extensive river systems and mangrove communities make the Kimberley region not well suited to supporting a major barramundi fishery (Anon., 1988). As a result the barramundi fishery in Western Australia has historically been relatively small.

Status of harvest over the last 30 years

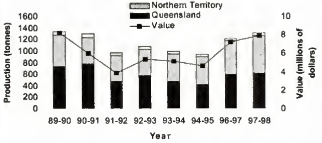
Past commercial landings

Figure 3 shows the production and value of the barramundi fishery in Australia from 1989/90 to 1997/98. Queensland and the Northern Territory are the largest producers whereas the fishery in Western Australia is relatively small.

Queensland

In 1981 a compulsory catch-log scheme was introduced into the Gulf of Carpentaria limited-entry gillnet fishery with a similar scheme introduced on the east coast in 1984. Prior to 1981 there was no official monitoring of total commercial barramundi catches in Queensland. Williams (1997) reports that from 1989 to 1995, about 300 commercial boats recorded barramundi catches and that about one-third of

FIGURE 3. Production (by state) and total value of the Australian barramundi fishery between 1989–90 and 1997–98



these boats operated in the Gulf of Carpentaria limited-entry fishery. In an analysis of commercial logbook data, Williams (1997) noted that there had been a decline in the commercial catch from 672 tonnes in 1989 to 501 tonnes in 1995, with a peak catch in 1991 of 738 tonnes. However, whereas total catch on the east Queensland coast has declined, catch per unit effort (CPUE) has remained relatively constant. In the Gulf of Carpentaria Williams reports that both CPUE and total catch have declined for the period. The fishery is also strongly seasonal, with the greatest catches being recorded in the periods immediately prior to (September–October) and during and following (February–April) the wet season.

Northern Territory

Commercial barramundi fishing statistics are available for the Northern Territory from about 1972 when the total catch was 382 tonnes and peaked at 1054 tonnes in 1977 (Department of Primary Industry and Fisheries, 1991). It was during the late 1970s that CPUEs for barramundi showed a consistent downward trend (Fallu, 1996) as a result of an alarming increase in fishing effort (Pender, 1995). This prompted the introduction of legislation regulating effort and CPUE, the latter being considered a significant indicator of the health of the fishery. As a result, the CPUE has improved and remained more or less steady since the late 1980s (Pender, 1995; Fallu, 1996). In 1996 in the Northern Territory there were 28 fully transferable commercial fishing licences, which accounted for a total barramundi catch of 542 tonnes, an increase over catches in 1995 (502 tonnes) and 1994 (447 tonnes) (Fallu, 1996). The recent trend of increased catches may have been the result of greater availability of barramundi or greater efficiency on the part of the commercial fishers. Fallu (1996) estimated that in 1996 at the point of first sale, the commercial component of the barramundi fishery was valued at A\$2.8 million. Since the 1970s, the extent of exploitation by recreational fishers has increased significantly along with population growth and development of previously remote areas (Grey, 1986). Grey (1986) also noted an increased community awareness of the economic benefits of recreational fishing, particularly through tourism, which resulted in the active promotion of barramundi fishing as a tourist attraction. In the mid-1980s, in recognition of the growing importance and impact of recreational fishing on the resource, measures were adopted to place further restraints on commercial fishing activity (Grey, 1986).

Western Australia

By comparison with Queensland and the Northern Territory, the commercial barramundi fishery in Western Australia is relatively small with only about five active licences in the northern Kimberley district and an annual production of about 50 tonnes (Anon., 1995). A report by the East Kimberley Recreational Fishing Advisory Committee estimated the value of recreational fishing on the Ord River (1996) to be worth in excess of A\$1.1 million (R. Doupé, personal communication).

FISHERY MANAGEMENT

The three Australian states and territory where barramundi fisheries exist have engaged their own individual strategies for management of their fisheries. However, there are a number of common themes including seasonal and area closures, gear restrictions, recreational angler bag limits and size limits on fish. In general, commercial fishers are restricted to operating in specific tidal waters although recreational and indigenous anglers and tour operators can fish in most tidal and non-tidal waters. Specific management regulations pertaining to barramundi in Queensland, Western Australia and the Northern Territory are detailed below.

Queensland

"The Queensland Department of Primary Industries" formerly the "Queensland Fisheries Management Authority" (QFMA) is the agency responsible for controlling commercial and recreational fishing activities. Other states and territories have similar organizations or government departments that are responsible for the administration of fisheries legislation. The objective of the Queensland legislation is to ensure that fisheries resources are used in an ecologically sustainable way to achieve optimum community economic and other benefits obtainable through fisheries resources to ensure access to fisheries resources is fair (QFMA, 1996). Management of fisheries in Queensland is essentially through control of effort rather than control of harvest (QFMA, 1996). In Queensland's *Fisheries Act* (1994), there are a number of key management measures pertaining to inshore fisheries. These include:

- a closed season on barramundi from 1 November until 31 January inclusive on the east Queensland coast and October to January in the Gulf of Carpentaria. The exact timing of the closure in the Gulf of Carpentaria is variable and tied to moon phase in order to maximize the number of barramundi spawnings in the closure period (Williams, 1997);
- prohibition on the use of river-set gillnets during the closed season on the east coast and all nets in the Gulf of Carpentaria;
- a recreational bag limit allowing fishers to have only five barramundi in their possession at any one time;
- minimum and maximum mesh sizes and limitations on the total number of nets in the commercial fishery;
- a weekend closure to commercial fishing from 18.00 hours Friday to 18.00 hours Sunday on the east coast;
- minimum (58 cm total length) and maximum (120 cm total length) size restrictions; and
- area closures for commercial fishers in some rivers.

Recently there have been changes to fishing regulations to account for the management of new impoundment recreational barramundi fisheries that have been created as a result of stocking activities. Barramundi impoundment fisheries in Queensland are solely "put and take" fisheries and as such anglers have argued that some of the regulations, which pertain to the natural fisheries, are inappropriate. As a result, in two impoundments barramundi fishing is conditionally permitted all year round and the maximum size restriction of 120 cm has been revoked, although the minimum size and bag limit still apply (QFMA, 1998). There is a prospect that similar operational guidelines may be extended in the future to other freshwater impoundments with developing fisheries. Although there is presently no provision for recreational licences in Queensland, recreational fishers need to purchase a permit to catch barramundi from certain stocked impoundments (QFMA, 1998).

When considering stock enhancement programmes, the QFMA must act in accordance with the principles of ecological sustainable development, maintenance of biodiversity and the precautionary principle (Cadwallader, 1997). Furthermore, Cadwallader (1997) states that the associated benefits and risks of all stocking programmes must be stringently appraised to minimize risk of irreversible damage to existing fisheries resources and the ecological systems on which these resources depend.

Northern Territory

The barramundi fishery is the highest valued fishery in the Northern Territory, with major recreational and commercial sectors but also with traditional Aboriginal people, fishing tourism and aquaculture as important user groups (Pender, 1995). Barramundi wildstocks in the Northern Territory are regarded as a common property resource and, as such, the basic responsibility of fisheries managers is to manage the fishery in the interests of the general community (Lea, Grey and Griffin, 1987). Lea, Grey and Griffin (1987) also assert that management must be consistent with the dual aims of maximizing the net economic benefits from the fishery while maintaining long-term viability of population levels of barramundi throughout its range.

The history of barramundi management in the Northern Territory dates back to 1962 when, in recognition of recreational fishing interests, all freshwaters were closed to gillnetting and traps between April and December (Pender, 1995). Since then there has been a voluntary licence buy-back scheme and numerous regulatory changes were adopted both before and with the establishment of the Barramundi Fishery Advisory Committee in 1990 and the Barramundi Management Plan in 1991 (Department of Primary Industry and Fisheries, 1991; Pender, 1995). In 1996, there were 28 fully transferable licences in the commercial fishery but recreational anglers are presently not required to pay licence fees (Pender, 1995; Fallu, 1996). Management measures (Pender, 1995; Fallu, 1996) include:

- commercial fishers are prohibited from fishing inside the mouths of most rivers and fishing activity is limited to three nautical miles seaward of the low-water mark;
- gear restrictions on commercial fishers include restrictions on mesh size and total length of net;
- area and seasonal closures apply to recreational fishers on the Mary and Daly rivers;
- recreational fisher bag limits of up to five fish per person (fewer in some areas).

Western Australia

In Western Australia, barramundi have a distinct distribution as far south as the Asburton River but the regulated commercial net fishery is primarily in the Kimberley district (north of, 19°S) (R. Doupé, personal communication). Barramundi caught south of this latitude are regarded as a bycatch of other fisheries. For management purposes the fishery is divided into the west and east Kimberley. In the east Kimberly division there is a closed season between December and January inclusive and a net licence allows for the use of 500 m of 112–150 mm mesh. The west Kimberly division has a slightly different closed season (November to January inclusive) and net size of 500 m of 165–177.8 mm stretched mesh.

There were no recreational fishing limits for barramundi until 1995 (R. Doupé, personal communication) when a minimum size limit of 550 mm and bag limit of five fish per person was adopted (R. Doupé, personal communication). Since November 1997, this has been modified for the Ord River region where there is now a size slot limit of 550–800 mm TL and a bag limit of one fish per person (Doupé, 1997). There are no licence requirements.

Outside Queensland, there has been no stock enhancement of barramundi in open river systems carried out to date. There have, however, been attempts to establish an impoundment fishery for barramundi in the Northern Territory. In the mid 1990s about 200 000 barramundi fry were released into Manton Dam on the Adelaide River (R. Griffin, Northern Territory Department of Primary Industry and Fisheries, personal communication). In 1999, a further 3 500 and 1 500 80- mm-long fish were released into Manton Dam and Lake Bennett respectively (G. Schipp, Northern Territory Department of Primary Industry & Fisheries, personal communication). There have been no sanctioned releases of barramundi in Western Australia although Doupé and Bird (1999) suggest that there have been occasional and illicit stockings of barramundi over many years into Lake Kunnunurra in the north of the State. They report that the fate of these releases and the number of resident fish are unknown although occasionally a capture is documented. Doupé and Bird (1999) noted an interest from community groups and government agencies in the development of a recreational barramundi fishery in impounded waters in northern Western Australia.

Aquaculture

The barramundi aquaculture industry in Australia had its beginnings in Queensland in the late 1980s when the Department of Primary Industries established a research programme aimed at adapting Thai culture techniques for Australian conditions (MacKinnon, 1987). Initially eggs for the programme were sourced from wild stocks and the larvae grown out to fingerling size in the hatchery using intensive culture techniques (MacKinnon, 1987). The production technology for barramundi has since developed so that now eggs are sourced from captive broodstock and both extensive and intensive systems are used for larval rearing (see Methodology of sea ranching section).

Barramundi are farmed in cages in freshwater or brackishwater ponds, in sea cages and in land-based recirculating systems (Rimmer, 1995b). Within the natural distribution of barramundi (Queensland, the Northern Territory and Western Australia) they are farmed in ponds or in sea cages. In southern Australia (New South Wales, Victoria and South Australia), where water temperatures are too low for successful outdoor farming of barramundi, they are farmed in indoor recirculating systems or using geothermal water.

The cages commonly used in pond culture are 8 m^3 in size ($2 \times 2 \times 2$ m), although larger cages (12–100 m^3) are also used. In ponds, two rows of cages are floated either side of a central walkway, which allows access for feeding and cage maintenance. Each cage is supplied with aeration to maintain a high dissolved oxygen concentration, and injector-type aerators are placed in the ponds to assist with water circulation and to increase dissolved oxygen levels (Rimmer, 1995b). Water exchange rates in ponds vary considerably between different farms, but generally range from 10 to 20 percent of pond volume per day. Sea cages used for barramundi culture are usually sited in estuarine areas where wind and wave action are greatly reduced, and are generally of the "polar cirkel" type originally developed for salmon culture (See Plate 4). Some barramundi are also farmed in earthen or lined ponds without cages, a technique known in Australia as "free-ranging". This technique is reported to result in faster growth and better appearance and colour (silver rather than black) of the fish, and reduces operational costs because cage maintenance is unnecessary. Because of bird predation problems with smaller fish in ponds, the use of "free-ranging" is largely restricted to larger fish (> 1 kg). The major disadvantage of this technique is the difficulty in harvesting the fish without draining the pond. Fish are captured using angling techniques, trapping or seine netting (Rimmer, 1995b).

PLATE 4. A "polar cirkel" type cage used for barramundi farming in an estuary in Australia

In Australia, a number of barramundi farms have been established using recirculating freshwater or brackishwater systems with a combination of physical and biological filtration. One farm in South Australia uses geothermal heated water for barramundi farming. The major advantage of these indoor culture systems is that they can be sited near to markets, thus reducing transport costs for the finished product.

Stocking densities used for cage culture of barramundi generally range from 15 to 40 kg/m^3, although densities may be as high as 60 kg/m^3 (Rimmer, 1995b). Barramundi are fed on commercially available pellets. Several Australian manufacturers now supply pellets developed specifically for barramundi, and a floating/slow-sinking pellet is now available. The use of floating pellets reduces feed wastage because they are available to the fish for longer, and the fish farmer can more easily observe the decreased rate of feeding that signals satiation.

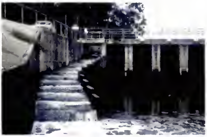
Most farmed barramundi are marketed at "plate size", i.e. 300–500 g weight. Recently, some farms have begun to produce larger fish (about 3 kg) for fillet product (Barlow, Williams and Rimmer, 1996). Growth is highly variable, and depends on various factors including feeding rate, feed quality and stocking density. Generally, barramundi grow from fingerling to 300–500 g in 6–12 months, and to 3 kg in 2 years. No significant differences in growth rate have been found in barramundi cultured in either fresh or salt water (MacKinnon, 1990). Similarly, there appear to be no substantial differences in the growth rates of barramundi from different genetic stocks.

Queensland is the largest producer of farmed barramundi amongst Australian states. In 1997/98, Queensland barramundi farms produced 434 tonnes valued at $A4.34 million (Lobegeiger, 1999). Total barramundi production for Australia is of the order of 600 tonnes valued at around $A6 million.

PRINCIPAL PROBLEMS WITH FISHERY

There is considerable concern about declining barramundi stocks not only in parts of northern Australia (Russell, 1988; QFMA, 1996; Williams, 1997) but also in other parts of the region including Papua New Guinea (Milton *et al.*, 1998). The reasons why barramundi are threatened are complex and related to numerous factors including overexploitation, habitat destruction, pollution and poor land management practices. Recently in Queensland, Williams (1997) has documented a general decline in commercial barramundi catches, although this has varied, particularly as a result of varying levels of effort. For example, on the east coast the total barramundi catch has declined whereas CPUE has remained relatively stable. However, in the Gulf of Carpentaria, both the total catch and the CPUE have declined There has been an upward trend in both catch and CPUE in the Queensland barramundi fishery during the late 1990s. Williams (1997) warns of a number of concerning biological indicators including changing population sex ratios, a diminishing mean size of female fish at sexual maturity that suggest that stocks in the Gulf of Carpentaria are under pressure. Additionally, he points to logbook data and research surveys that show

PLATE 5. Fishway on a tidal barrage on the Burnett River in central Queensland. This type of step and pool fishway is unsuitable for many native Australian fish including barramundi



that between 60 and 70 percent of the barramundi harvested are sexually immature at capture and that fishing operations are largely based on barramundi that have grown just large enough to enter the fishery. This is of major concern, considering that Milton *et al.* (1998) regard barramundi populations as highly susceptible to recruitment overfishing and view the dramatic decline in catch levels of barramundi in the Western Province of Papua New Guinea as evidence of recruitment overfishing. In the Northern Territory, Fallu (1996) noted that barramundi populations have largely recovered from previous overexploitation, which dated back as far as the late 1970s.

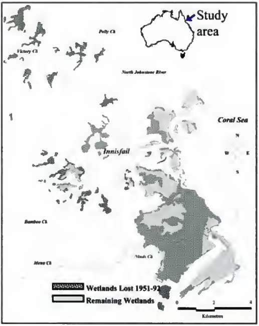
One of the major problems associated with development of effective management plans is a paucity of information for management of the fishery. For example, whereas there are reasonable data on the levels of exploitation in the commercial fishery (Lea, Grey and Griffin, 1987; Quinn, 1987; Fallu, 1996; Williams, 1997) there is little information on either recreational or indigenous catches. Fallu (1996) notes that barramundi is used as a food source for Aboriginal people in coastal areas of the Northern Territory but that the level of utilization is unknown. In an earlier study, Lea, Grey and Griffin, (1987) describe indigenous users as having only a small impact on the fishery in the Northern Territory. The situation is similar in Queensland where the indigenous catches are unknown, although Williams (1997) believes that catches of fisheries resources may be substantial in some areas. The recreational catch of barramundi in Queensland remains unknown (Williams, 1997) whereas in the Northern Territory there have been a series of area-specific angler surveys (Griffin, 1993; Fallu, 1996). In one area of these surveys, the total catch rate was shown to have increased from 0.11 fish/hour in 1986 to 0.23 fish/hour in both 1994 and 1995. Little information is available on the barramundi fisheries in Western Australia.

Lea, Grey and Griffin (1987) assert that to achieve management objectives it is first necessary to obtain estimates of what yield can be sustained by the fishery. Apart from a lack of reliable population parameters for the fishery, they maintain that one large problem faced by managers when aiming to assess the maximum sustainable yield is the lack of data from recreational fisheries. In Queensland, a discussion paper on the Gulf of Carpentaria inshore fishery (QFMA, 1996) concedes that there is insufficient knowledge to demonstrate whether present harvest levels of target species, including barramundi, are sustainable. Furthermore, it admits that sustainable harvest levels are unlikely to be identified for many years. In the absence of definitive data on sustainable harvest levels, the discussion paper maintains that the principles of ecologically sustainable development require that responsible fisheries agencies take a precautionary approach to maintain biological diversity, provide for sustainable use of fisheries resources and ensure the equitable use and allocation of natural resources within and between generations (QFMA, 1996).

With a number of competing industry sectors, it is not surprising that resource sharing is an issue, particularly between the commercial and recreational fishers (Grey, 1986). Although catch statistics for the recreational fishery are either inadequate or non-existent, there is little doubt that increasing populations in regional centres, improved accessibility to fishing grounds and more leisure time are shifting the balance in favour of the recreational fishery. For example, in the Northern Territory, the recreational fishery expansion occurred rapidly and by the early 1980s the annual value of the fishery was about the same magnitude as the commercial catch (Grey, 1987). As a consequence of this shift, the management regulations were subsequently adjusted to take account of the recreational component. Grey (1986) noted that there was also an increasing awareness of the economic benefits of recreational fishing, particularly through tourism, and this had resulted in the active promotion of barramundi as a tourist attraction. Significantly, he suggested that when aquaculture production reaches the point of commercial production, much of the commercial demand for the species to be taken from wild stocks will be alleviated.

Development including urbanization, agricultural expansion and an extension of infrastructure to cater for a developing tourist industry are combining to put further pressure on the resource. As described in the Life history and reproductive biology section, barramundi are catadromous and euryhaline, utilizing a range of estuarine coastal and freshwater habitats. Moore (1982), Davis (1985a, 1985b) and Russell and Garrett (1983, 1985) found barramundi postlarvae utilize specific nursery habitats adjacent to estuaries and coastal spawning grounds. Russell and Garrett (1985) suggested that human interference with nursery grounds could lead to a decline in local barramundi stocks and their attendant fisheries. They conjecture that, if a direct relationship exists between nursery areas and barramundi stocks, then it is fortuitous that, with the exception of the east Queensland coast, much of northern Australia is still isolated, sparsely populated and industrially undeveloped. In eastern Queensland in particular, urban, agricultural, tourist and industrial development have impacted on fisheries habitat. In some catchments more than 60 percent of freshwater wetlands (Russell and Hales, 1993; Russell, Hales and Helmke, 1996a, 1996b) (see Figure 4) have been lost primarily to agricultural

FIGURE 4. Loss of coastal wetlands from the Johnstone catchment in northeastern Queensland between 1951 and 1992. Russell and Hales (1992) estimated that in this period about 60 percent of the wetlands were lost to mostly agricultural development



development. There has been further habitat loss through the construction of barrages and dams on coastal rivers, many of which do not make adequate provision to facilitate fish passage (See Plate 5) and alter hydrological and nutrient processes (QFMA, 1996). Agricultural practices in estuary catchments have destroyed riparian zones, and pesticides, fertilizers and sediments have had adverse impacts on fisheries production (QFMA, 1996).

These changes have been occurring progressively over many years and although processes such as Integrated Catchment Management in Queensland are now helping to address some of the environmental issues, many are regrettably irreversible. In such situations where habitat restoration is improbable or impossible and where traditional restrictions on fishing effort are ineffective, stock enhancement is a potentially productive management tool.

UNIQUE FEATURES OF FISHERY

The commercial barramundi fishery in Australia is the major component of a broader multispecies coastal and estuarine gillnet fishery (Russell, 1988). The total production (over 1300 tonnes in 1997/98) by world standards is relatively small, but the product commands high prices and is in high demand. The fishery comprises a number of smaller, individual licensed operators rather than larger, company-owned fleets that characterize many other fisheries. Attempts have been made to take into account the complex biology of barramundi in the development of the management strategies. For example, in Queensland the closed season is designed to protect fish during the period when spawning activity is greatest. In the Gulf of Carpentaria fishery, this has been fine-tuned to the point where moon phase determines the opening and closing of the season (QFMA, 1996). Management regulations for the fishery also take into consideration that Barramundi are protandrous hermaphrodites that mature as males and later change sex to females (Davis, 1985a). In Queensland there is not only a minimum size limit (58 cm) designed to allow fish to mature as males but there is also a maximum size (120 cm) to protect larger, breeding females (QFMA, 1996).

RATIONALE BEHIND SEA RANCHING/ENHANCEMENT

Why was sea ranching chosen?

In Australia, impoundment stockings preceded sea ranching of barramundi. Barramundi were first stocked in impoundments in Queensland with the purpose of creating new recreational fisheries in waters that would otherwise have had only limited fishing potential (MacKinnon and Cooper, 1987). Originally it was proposed to create a recreational fishery in artificial impoundments through the introduction of Nile perch (Midgely, 1968). The rationale for this action was that most Australian freshwater fishes have adapted to riverine conditions, and hence their biology is geared to lotic environments (Barlow, 1984). However, the risks associated with this proposed introduction were considered to outweigh the potential benefits and consequently the responsible agency abandoned the concept of introducing Nile perch to Australia (Barlow and Lisle, 1987). Coincidentally at this time the technology for mass production of barramundi fingerlings was being developed in a number of Queensland hatcheries (MacKinnon and Cooper, 1987) thus providing the prospect of large number of fingerlings being available for stocking into the wild. Instead of the creation of fisheries based on Nile perch, a successful programme was developed to create "put and take" barramundi fisheries in north Queensland impoundments

(Pearson, 1987). This stocking programme was later extended to include open river systems to address perceived declines in natural stocks that arguably are the result of multiple factors including habitat degradation and overexploitation (Rimmer and Russell, 1998b). The first open river system was stocked with hatchery-reared barramundi in 1990 and since then fish have been released into many east coast streams and in the Gulf of Carpentaria drainage system (Rimmer and Russell, 1998b). The fishing community, particularly recreational fishers, is strongly supportive of the concept of barramundi stock enhancement and they have taken the initiative and formed numerous community-based stocking groups (Rimmer and Russell, 1998b). These groups both aggressively promote and are actively involved in the release of barramundi and other species into impoundments and coastal streams. Community stocking groups in Queensland source their fingerlings from both government and commercial hatcheries.

In Australia, Queensland is currently the only state where sea ranching of barramundi is being promoted. A research project is underway in Queensland that is investigating the efficacy and cost-effectiveness of sea ranching (Rimmer and Russell, 1998b). In the Northern Territory, there has been some limited stocking of a freshwater impoundment but no stocking programmes have been instigated in coastal rivers (Doupé and Bird, 1999, R. Griffin, Northern Territory Department of Primary Industry and Fisheries, personal communication). Similarly, in Western Australia there have been no sanctioned releases of barramundi in either impoundments or in coastal rivers, although Doupé and Bird (1999) suggest that there have been occasional illicit stockings of barramundi over many years. Harvest and environmental pressures on barramundi stocks in the Northern Territory and north Western Australia are likely to be considerably lower than those in Queensland because of the lower human population densities and limited development, so the need for stock enhancement in these areas is limited (Rimmer and Russell, 1998b).

Evaluation of other fishery management options

In Queensland, fishery management plans are viewed as fluid documents, and the agency responsible for the management of the barramundi fishery (the QFMA) conducts regular reviews of the fishery management plan (e.g. QFMA, 1996). However, if an issue arises mid-cycle that requires immediate attention, then there is provision for it to be addressed outside the regular review process (e.g. QFMA, 1996).

In most states there are now mechanisms in place that seek to protect remaining fish habitat. For example, in Queensland, legislation provides for the proper management, use, development and protection of fish habitats (Couchman, Mayer and Beumer, 1996). This is being done through the protection of all marine plants, the gazette of Fish Habitat Areas to protect critical habitats and, where appropriate, the restoration of damaged or destroyed habitats of importance to fisheries stocks (Couchman, Mayer and Beumer, 1996).

Cadwallader (1995) suggests that if barramundi breeding grounds have been degraded or destroyed, then stocking may be an appropriate strategy for increasing stock numbers. However, he qualifies this by suggesting that habitat rehabilitation of breeding and nursery areas may be a much better long-term option than an ongoing stocking programme. The extent of the loss of wetland habitat, particularly in eastern Queensland, is documented above and this has undoubtedly impacted on barramundi nursery areas. There is a case for remedial works to address some of these losses and Tait (1995) cites cases where activities such as creation of artificial wetlands are contributing to the rehabilitation of coastal fish stocks. However, in comparison with the scale of the original losses, most of which are permanent, such activities are likely to provide only minimal short-term benefits. Furthermore, ignoring the substantial costs of such a programme, it would appear highly unlikely that any significant tracts of now productive agricultural land would be available for habitat rehabilitation.

METHODOLOGY OF SEA RANCHING

Broodstock selection and management

Barramundi brood fish are collected from the wild using gillnets or electrofishing techniques. The latter is preferred because it causes less physical damage to the fish than gillnets. Because of the increasing numbers of hatchery-reared fish being stocked into eastern Queensland drainages, it is becoming progressively more difficult to guarantee that brood fish caught from the wild are not hatchery-reared fish. In some river systems (e.g. the Johnstone River, near Innisfail) all stocked fish are tagged with coded wire tags (Rimmer and Russell, 1998b), but in most Queensland rivers this is not the case.

Barramundi brood fish are held in fibreglass or concrete tanks (see Plate 6) that range in size from 20 to 200 m^3 and which may operate on either flow-through or recirculating water supply systems. Stocking density in tanks is around 0.5 fish/ m^3, and sex ratios are maintained at about 1 : 1 to 2 : 1 (male to female). Commercial farms may hold "spare" broodstock (i.e. those not currently used for spawning) in cages (Plate 4). Barramundi brood fish are fed once daily at a rate of 1–2 percent of body weight (BW), or three times weekly at 3 percent BW, using commercially available baitfish. Because baitfish may not be well handled or stored between capture and sale, their nutritional quality is often poor. Vitamin supplements are usually added to the baitfish to improve the nutritional composition of the brood fish diet, and prevent diseases associated with vitamin deficiencies. Squid and prawns may also be added to the diet.

PLATE 6. Barramundi broodstock held in a saltwater tank at the Northern Fisheries Centre, Cairns, Queensland

Because of the relatively large size of adult barramundi (females are generally 10–20 kg in weight), facility size limits the number of fish that can be kept for broodstock purposes. As a result of this, no Australian hatchery (including government hatcheries) currently has the facilities to hold the large numbers of broodstock typically recommended for marine stock enhancement programmes (Allendorf and Ryman, 1987). In general, many captive barramundi do not mature sufficiently to be used as brood fish, and there is some evidence that this proportion varies between different genetic strains. As a "rule of thumb" in Queensland, only about 25 percent of Cairns strain barramundi mature to the point at which they can be induced to breed, whereas this proportion is much lower (<10 percent) for southern Gulf of Carpentaria strain fish kept under identical conditions. Similar low proportions of maturing broodstock have been reported for other marine finfish species, such as red drum *Sciaenops ocellatus* (Tringali and Bert, 1998).

Spawning induction

Barramundi brood fish may be kept in either fresh or salt water but must be placed in salt water (28–35 ppt) prior to the breeding season to enable final gonadal maturation to take place. Barramundi show no obvious external signs of gonadal development and must be examined by cannulation to determine their gender and reproductive status. The cannula is a 40–50 cm length of clear flexible plastic tubing (3 mm outer diameter, 1.2 mm inner diameter) that is inserted into the urinogenital orifice of males or the oviduct of females after they have been anaesthetized. The cannula is guided into the fish for a distance of 2–3 cm (males) or 6–7 cm (females), and suction is applied to the other end of the cannula as it is withdrawn. After withdrawal, the sample within the cannula is expelled onto a Petri dish or, in the case of eggs, into a vial containing 1–5 percent neutral buffered formalin for later measurement of egg diameter (Garrett and Connell, 1991).

Although environmental manipulation has been used with success to induce spawning in Asian populations of barramundi (Rimmer and Russell, 1998a), Australian populations can only be reliably induced to spawn using exogenous hormone preparations. Barramundi females with eggs 400 µm in diameter or larger are suitable for hormonal induction of spawning; males that are suitable for spawning induction will indicate milt (dense sperm) when cannulated or may produce a small "bead" of milt when moderate external pressure is applied to the belly of the fish (Garrett and Connell, 1991). Barramundi brood fish are usually suitable for spawning induction when water temperatures reach or exceed about 28 °C.

Barramundi have been successfully spawned using a range of hormones at various doses, which are administered by various techniques including injection, slow-release cholesterol pellets and osmotic pumps; but spawning induction is now generally carried out using the leuteinizing hormone-releasing hormone analogues (LHRHa) (Des-Gly^{10})D-Ala^{6},Pro^{9}-LH-RH ethylamide and (Des-Gly^{10})D-Trp6,Pro^{9}-LH-RH ethylamide (Garrett and Connell, 1991). Hormones are injected intramuscularly at the base of the pectoral fin. LHRHa dosages of 3–5 µg/kg body weight usually produce a single spawning, whereas dosages of 10–25 µg/kg usually produce 2–4 spawnings on consecutive nights (Garrett and Connell, 1991). Females only are injected; males do not usually need to be induced.

Fish are injected with hormones in the morning to allow for natural spawning in the evening of the following day. Prespawning behaviour involves the male fish pairing with a female and rubbing its dorsal surface against the area of the female's genital papilla, erecting its fins and "shivering". In the absence of such displays, egg release may occur but the eggs are not fertilized. Spawning occurs 34–38 hours after injection, usually around dusk (Garrett and Connell, 1991).

Barramundi will often spawn for up to five consecutive nights (Garrett and Connell, 1991). In the case of spawnings on consecutive nights, egg production, fertilization rate and hatching rate are normally higher on nights 1 and 2 than on subsequent nights; eggs from spawnings on nights 3 and 4 are frequently discarded because of low fertilization and hatching rates. Fecundity is high and females may produce in excess of 0.4 x-10^{6} eggs/kg; it is not uncommon to obtain 3–4-x-10^{6} eggs from a single night's spawning by a single female barramundi.

FIGURE 5. Newly hatched barramundi larvae. Yolk sac and oil globule are clearly visible. (Drawing by Kirsten Otlee)

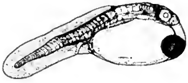
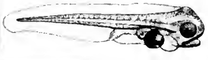


FIGURE 6. Barramundi larvae approximately 3 mm long. Yolk sac has almost completely reabsorbed. (Drawing by Kirsten Otlee)



The breeding season of barramundi can be extended indefinitely by the provision of summer water temperatures (≥-28-°C) and day length (≥-13-h light). Fish subjected to this regime can be induced to spawn at monthly intervals throughout the year, and do not change sex (Garrett and O'Brien, 1993).

Harvesting eggs

At spawning, the sperm and eggs are released into the water column and fertilization occurs externally. Barramundi eggs are 0.74–0.80 mm in diameter with a single oil droplet 0.23–0.26 mm in diameter (NICA, 1986). The fertilized eggs may be positively or neutrally buoyant; unfertilized eggs are generally negatively buoyant (NICA, 1986).

Barramundi eggs are concentrated in the spawning tanks using egg collectors, either inside or outside the tanks. Internal egg collectors consist of bags of 300 µm mesh material, approximately 0.5 m^3 in volume, which are suspended from a hollow PVC frame. Eggs are concentrated in the net using airlifts fitted to the PVC frame. External egg collectors are suitable only for flow-through tank systems and are placed in externally mounted tanks through which the tank effluent passes.

Eggs are placed in larval rearing tanks at densities of up to 1 200 eggs/litre for incubation and hatching. Dead and unfertilized eggs are removed by briefly turning off the aeration in the hatching tank and siphoning out the dead eggs, which sink rapidly to the bottom of the tank.

Egg and larval development

Fertilized eggs undergo rapid development and hatching occurs 12–17 h after fertilization at 27–30 °C (FAO, 1984; NICA, 1986; Ruangpanit, 1987; Parazo *et al.*, 1990). Newly-hatched larvae (Figure 5) have a large yolk, which is absorbed rapidly over the first 24 h after hatching, and is largely exhausted by 50 h after hatching (Kohno, Hara and Taki, 1986). The oil globule is absorbed more slowly and persists for about five days after hatching. The mouth and gut develop the day after hatching (day 2 [D2]) and larvae commence feeding from 45 to 50-h after hatching (Kohno, Hara and Taki, 1986; Parazo *et al.*, 1990) (Figure 6).

Larval rearing

Barramundi are reared to fingerling stage generally ≥20 mm (TL) using either intensive rearing techniques (Rimmer and Russell, 1998a).

Intensive larval rearing

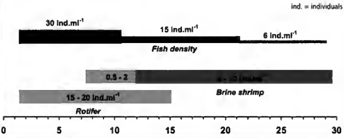
Barramundi larvae are reared intensively in circular or rectangular fibreglass or concrete tanks of up to 5 m^3 capacity. Circular tanks with a conical base are preferred because of better water circulation and drainage compared with rectangular tanks (Russell, 1987). Rearing tanks are constructed with a central bottom outlet fitted with a removable screen to retain larvae (Russell, 1987). Recommended stocking rates for barramundi larvae (up to about 10 mm TL) are 10–40 fish/litre. Overall survival for intensively reared barramundi larvae from hatching to about 10 mm TL is usually around 50 percent.

Both "clear water" and "green water" intensive rearing techniques have been successfully used to rear barramundi (Palmer *et al.*, 1992; Rimmer and Russell, 1998a). Using "clear water" techniques, optimal water quality is maintained by having high rates of water exchange to remove wastes, particularly ammonia. The water supply may be from flow-through or recirculating systems. In "green water" culture, a microalgal culture (usually *Nannochloropsis oculata* or *Tetraselmis* sp.) is added to the rearing tanks at densities ranging from 8–10-× 10^3 to 1–3-× 10^5 cells/ml and the microalgae aid in maintaining optimal water quality by utilizing nitrogenous wastes and carbon dioxide, and producing oxygen. To maintain the desired density of microalgal cells, water changes are limited to 10–50 percent daily for the first 25 days of the rearing period, and 50–75 percent daily thereafter. Rearing tanks are siphoned clean daily, and microalgal cultures are added to maintain the required density of algal cells.

Intensively reared barramundi are fed on rotifers (*Brachionus plicatilis*) from D2 (where D1 is the day of hatching) until D10 (or as late as D15), and on brine shrimp (*Artemia* sp.) from D8 onwards (Rimmer *et al.*, 1994) (see Figure 7). Rotifers are fed 2–4 times daily, at 10–20 individuals/ml. Brine shrimp are fed 2–3 times daily at 0.5–2 individuals/ml initially, gradually increasing to 5–10 individuals/ml.

An important requirement for intensively reared barramundi larvae is adequate nutrition. Barramundi larvae fed diets deficient in highly unsaturated fatty acids (HUFA), particularly 20:5n-3 (eicosapentaenoic acid or EPA), become pale and, when stressed, swim erratically and "faint", after which they either recover (presumably temporarily) or die (Dhert *et al.*, 1990; Rimmer *et al.*, 1994). Feeding procedures developed to overcome this deficiency provide prey organisms of suitable nutritional quality. Rotifers are cultured using microalgae high in HUFAs such as *Nannochloropsis oculata*, which is high in EPA. Both rotifers and brine shrimp may be supplemented with a commercially available HUFA enrichment preparation in liquid or microcapsule form (Dhert *et al.*, 1990; Rimmer *et al.*, 1994).

FIGURE 7. Density of fish and prey for intensive rearing of barramundi larvae



Extensive larval rearing

In Australia, ponds used for the extensive larval rearing of barramundi generally range from 0.05 to 1 ha in area and may be earthen or plastic-lined (see Plate 7) (Rimmer and Russell, 1998a). They are relatively shallow (< 2 m deep) to promote maximum production of phytoplankton and to prevent stratification. The productivity of a pond is controlled by the addition of organic and inorganic fertilizers, which generate the blooms of phytoplankton, bacteria and protozoans that are food sources for zooplankton (Geiger, 1983a, 1983b). Although various inorganic and organic fertilizers can be used, the most commonly used fertilizers are diammonium phosphate (DAP) and lucerne pellets.

Barramundi larvae are stocked into the pond at the time they are ready to commence feeding (usually D2), to coincide with peak densities of the smaller zooplankton, i.e. rotifers and copepod nauplii, which are the initial prey of the larvae (Rutledge and Rimmer, 1991). The larvae are stocked at densities of 400 000–900 000 fish/ha (Rutledge and Rimmer, 1991).

Zooplankton density and water quality parameters, particularly dissolved oxygen, temperature, salinity and pH, are monitored routinely (Rimmer and Rutledge, 1991). Larval and juvenile barramundi are sampled regularly to determine the success of stocking, and to monitor growth and fish health (Rimmer and Rutledge, 1991). Barramundi larvae can be readily sampled from aerated ponds using a zooplankton net (35 cm diameter, 80 cm length, 300 µm mesh size). Juvenile barramundi are sampled using square lift nets 0.25–1.0 m^2 fitted with 1–2 mm mesh size insect screen or similar material. The lift nets are left on the bottom of the pond and are lifted rapidly to trap any juvenile barramundi that are on or directly above the net (Rimmer and Rutledge, 1991).

Barramundi in larval rearing ponds commence feeding on the smaller zooplankton, such as rotifers and copepod nauplii. As the larvae grow, they feed on larger organisms such as copepodites, adult copepods and (if present in the pond) cladocerans. As zooplankton densities decrease as a result of predation, the barramundi switch to benthic food sources, principally midge larvae "blood worms" (Rutledge and Rimmer, 1991).

Extensively reared barramundi larvae grow faster than larvae reared intensively, possibly owing to better nutrition resulting from a more varied diet and to greater prey availability throughout the day. Generally, extensively reared barramundi reach 20–30 mm TL after about three weeks in the pond, at which time they are harvested. By comparison, intensively reared barramundi reach about 10 mm TL after three weeks (Rutledge and Rimmer, 1991). Growth rates of up to 3.8 mm/day and specific growth rates (in length) of up to 28 percent/day have been recorded for extensively reared barramundi larvae. However, growth rates in ponds vary widely and are particularly dependent on water temperature, salinity and food availability. Barramundi are harvested from the ponds when they reach 20 mm TL or greater, and are then transferred to nursery tanks.

PLATE 7. A saltwater pond used for the extensive culture of barramundi. The pond is in the process of being drained prior to harvesting

Survival of extensively reared barramundi averages about 20 percent, but is highly variable, ranging from 0 to 90 percent These figures correspond to production rates of up to 640 000 fish/ha (Rimmer and Russell, 1998a). The lower costs of extensively reared fingerlings, estimated at 40–64 percent that of intensively reared fingerlings (Lobegeiger, 1993), and the lower infrastructure requirements for this technique have resulted in the widespread adoption of extensive larval rearing techniques for barramundi in northern Australia.

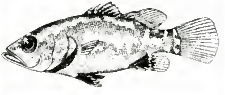
Nursery phase

Juvenile barramundi (Figure 8) are transferred to nursery facilities after they have been harvested from the rearing ponds, or from intensive culture tanks. Most nursery facilities use small cages (about 1 m^3) made from insect screen mesh in concrete tanks or above-ground pools. Many Australian barramundi farms use freshwater ponds for grow-out and thus operate freshwater nursery facilities (Rimmer and Russell, 1998a). Juvenile barramundi (> 10 mm TL) can be transferred from saltwater to freshwater in as little as 6 h with no significant mortality (Rasmussen, 1991).

Once they are in the nursery facility, the fingerlings are weaned to pellets. Barramundi can be weaned to pellet diets from as small as 10 mm TL, although better survival and faster acceptance of pellets are obtained if weaning is delayed until the fish are at least 15–20 mm TL (Barlow Williams and Rimmer, 1996). Barramundi may commence feeding on inert diets within a few hours of harvesting, and most fish commence feeding within a few days.

Barramundi fingerlings are usually supplied to stocking groups, or stocked out directly by the hatchery operator, from the nursery. Stocking of fingerlings directly from the rearing ponds does sometimes occur, but is not often undertaken because it is difficult to obtain an accurate count of the number of fish obtained.

FIGURE 8. Juvenile barramundi. (Drawing by Kirsten Otlee)



Release strategy

In Queensland, stocking groups purchase fish directly from commercial hatcheries, or are supplied by the state government hatcheries. Typically, barramundi of 20–40 mm TL are stocked, depending on the availability of fingerlings of various sizes. Barramundi fingerlings supplied by commercial hatcheries are sold on the basis of average size, generally for $A0.01 per mm TL. Because of this pricing structure, most stocking groups prefer to purchase larger numbers of cheaper (smaller) fingerlings. One stocking group in northern Queensland usually releases smaller numbers (thousands) of larger barramundi (about 150 mm TL), but there has been no objective comparison of this strategy with that of release of larger numbers of smaller fish.

Release sites are limited by the availability of access for the stocking trucks or transport vehicles (See Plate 8). In some cases, stocking groups may supply boats that are used to distribute the stocked fish more widely than the immediate access area. Preferred release sites for barramundi are those with abundant sublittoral vegetation and other structures to provide shelter for the stocked fish.

Unpublished results from our study in the Johnstone River in far northern Queensland indicate that there are substantial differences in survival of barramundi

PLATE 8. Barramundi being stocked into a north Queensland river

stocked at different sites. The site with the apparent best survival was a freshwater site that has extensive weed (*Vallisneria*) beds that provide excellent habitat for newly released juvenile barramundi. Survival from estuarine sites, despite the availability of extensive mangrove habitat, was much poorer.

Some sites have been found to be unsuitable for release of juvenile barramundi. One site in particular, a freshwater swamp, was stocked for three years with barramundi fingerlings but none has ever been recaptured. This is most likely because of periodic severe declines in water quality in the swamp, resulting in lethally low dissolved oxygen levels (Rimmer and Russell, 1998b).

Limited assessment of size-at-release has demonstrated no significant difference between recaptures of "small" (30–40 mm TL at release) and "large" (50–60 mm TL at release) barramundi (Rimmer and Russell, 1998b). Recently, this research has been expanded to include larger size classes of fish up to 300 mm TL at release. The results of this expanded experimental design have not yet been fully analysed, but it appears that there are proportionally larger numbers of the larger fish (300 mm TL at release) amongst sampled fish.

GENETIC RESOURCE MANAGEMENT

Stock structure

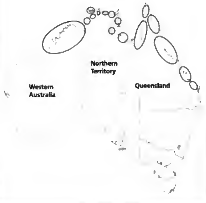
The genetic stock structure of barramundi wild stocks in Australia has been studied in detail by Shaklee and Salini (1985), Salini and Shaklee (1988) and Shaklee, Salini and Garrett (1993) and more recently by Keenan (1994). Using allozyme electrophoresis, Shaklee and Salini (1985) reported heterogeneity of barramundi populations in three widely spaced localities in northern Australia. In a later publication, Salini and Shaklee (1988) found genetically distinct barramundi stocks in seven of eight northern Australian locations from which samples were taken. Further sampling found that there were 14 distinguishable populations of barramundi in northern Australia (Shaklee, Salini and Garrett, 1993). A later study by Keenan (1994) differentiated a further two subpopulations of barramundi in the Northern Territory (Figure 9). Keenan (1994) showed that the largest differences in the population structure of barramundi in Australia were between those found on the east coast and stocks to the west. In addition, he suggested that certain populations from the east and west exhibited higher genetic variation than adjacent stocks because they were source populations prior to dispersal during periods of higher sea levels.

Salini and Shaklee (1988) noted that the existence of genetically discrete stocks of barramundi implied that either the geographical separation of such localities or the behaviour of barramundi in these areas, or both, was sufficient to restrict gene flow to a level incapable of overriding the effects of random genetic drift.

Translocation of non-indigenous genetic stocks

In Queensland, the potential problems associated with translocation of hatchery-reared barramundi derived from one genetic stock into another discrete genetic stock have been recognized by the QFMA. The QFMA has adopted elements of the "responsible approach" to fish stocking (Blankenship and Leber, 1995; Rimmer, 1995a) and any proposed stock enhancement programme requires the associated benefits and risks to be stringently appraised (Cadwallader, 1997). The aim is to enhance fisheries with minimal risk of irreversible damage to existing fisheries resources and the ecological systems on which these resources depend (Cadwallader, 1997). In its draft management plan and regulatory impact statement for Queensland freshwater fisheries (QFMA, 1998) the QFMA has adopted a set of translocation principles for assessing proposals for fish stock enhancement. The guiding principle (Cadwallader, 1997) is in stocking of public and private waters with translocated or non-indigenous genetic stocks of a species to be considered only where a clear economic, social or conservation benefit can be demonstrated, and where no alternative native species in the drainage basin has similar potential. Full details of the translocation principles are given in Appendix 1.

FIGURE 9. Genetic stock structure of barramundi in Australia. Sixteen distinct stocks have been identified. (Map adapted from drawings courtesy of C. Keenan, Queensland Department of Primary Industries)



Cadwallader (1997) describes the decision-making process for assessing stock enhancement or translocation proposals as a series of reviews, where failure to satisfy a particular criterion results in the rejection of that proposal. If the proposal satisfies the criterion then it is assessed against the next one, and so on. Genetic and disease risks form part of the assessment criteria.

Salini and Shaklee (1988) also warn of the danger of unmonitored mixing of barramundi from different stocks during hatchery releases for restocking programmes. They suggest that the consequence of mixing natural stocks and hatchery fingerlings derived from a small number of parents is a reduction of naturally occurring genetic diversity and fitness.

Broodstock management

Various aspects of the biology of barramundi in hatcheries affect genetic resource management of the species. Because of the high fecundity of barramundi (Davis, 1985a), only a relatively small number of adult fish need be maintained to supply hatchery demand. Brood fish held under ambient conditions will change sex from male to female, and the hatchery operator must regularly replace male fish to maintain a stock of spawning males (Garrett and O'Brien, 1993). Only a small proportion of these fish (both males and females) will mature sufficiently to produce viable gametes. However, with the development of year-round spawning techniques, only a small number of "good performers" need be held and these can be used for spawning for many years. In fact, most hatcheries rely heavily on a small number of "good performers" that are held under environmental control conditions and are often the major contributors to the genetic pool of the progeny. Based on these factors, inbreeding effects are likely to be high in many hatcheries.

Selective breeding

Commercial hatcheries in Queensland are keen to undertake selective breeding of barramundi to produce faster growing strains. Hatchery-reared broodstock (G1 and G2 generations) are reported to show some differences in their reproductive behaviour in captivity compared with wild caught (G0) fish. In particular, G1 and G2 fish do not exhibit the same response to environmental control conditions as G0 fish, but may change sex even under constant summer photothermal conditions. The Cooperative Research Centre for Aquaculture has supported research into the reproductive biology of captive barramundi broodstock to enable better control of these fish in hatchery environments as a necessary first step towards developing selective breeding programmes (Anderson *et al.*, 1998).

Some commercial farms have commenced mass selection programmes and report dramatically improved growth rates in their G1 and G2 fish. Unfortunately, these selection programmes have been designed without input from professional geneticists and are almost definitely based on small founder populations with little or no outbreeding. Because these same commercial hatcheries also sell fingerlings to local stocking groups, there is considerable concern among government researchers that severe bottlenecking of hatchery populations is taking place, and that these fish may adversely impact on wild barramundi populations if they are stocked in areas where the fish may contribute to breeding populations.

Fish health management

Barramundi larvae reared in Australian hatcheries have periodically suffered severe mortalities (up to 90 percent in some batches) at around D12–D14. Affected larvae became pale and swam erratically in a corkscrewing motion before dying (MacKinnon, 1987). Histological examination of the affected larvae showed extensive vacuolation of the brain and spinal chord and accumulation of excessive fat deposits in the liver (Rodgers and Barlow, 1987). The cause of these mortalities has been variously ascribed to nutritional deficiencies in the live food organisms fed to the barramundi larvae (Rodgers and Barlow, 1987) and to the action of a picorna-like virus in the larvae (Glazebrook, Heasman and de Beer, 1990; Glazebrook and Heasman, 1992; Munday *et al.*, 1992). Similar symptoms have been described for a mortality syndrome seen in sea bass larvae reared in Tahiti (AQUACOP, Fuchs and Nédélec, 1990; Renault *et al.*, 1991).

Infection of larvae with the barramundi picorna-like virus (since reclassified as a *nodavirus*) was readily controlled with improved hatchery methods and this virus then had little effect on barramundi production (Anderson *et al.*, 1993). However, there has been considerable concern about the possible transfer of this pathogen to native fish species inhabiting southern Australian waterways, via barramundi farmed in recirculation production facilities in southern states (New South Wales, Victoria and South Australia) where the barramundi does not naturally occur. In response, fisheries authorities in the southern Australian states have imposed health assessment measures to reduce the chance of barramundi nodavirus being introduced to local waters. These measures include:

- limiting barramundi hatcheries and farms to indoor recirculation systems, with strict controls on effluent;
- histological assessment of the health status of any batches of barramundi fingerlings imported from interstate; and
- requirement to notify fish health authorities in the event of a disease outbreak.

Further research is currently under way to examine the susceptibility of a range of native fishes to barramundi nodavirus, with a view to reviewing these management controls.

Columnaris disease (caused by bacteria of the *Flexibacter/Cytophaga* group) is a particularly important disease of barramundi in nursery facilities (Anderson and Norton, 1991). Columnaris disease typically occurs soon after fish are harvested from the larval rearing ponds and are introduced to the nursery tanks (usually within 24 h from harvesting). Health surveys of juvenile barramundi reared in ponds have shown that they are largely free of ectoparasites.

MONITORING AND EVALUATION PROGRAMMES

Enhancement goals

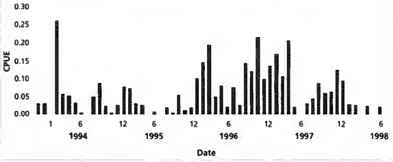
Prior to the commencement of stocking programmes, fishers in Queensland had expressed concern over perceived declines in barramundi populations (Rimmer and Russell, 1998b). Available evidence (see Principal problems with fishery section) seems to support this view, and although the reasons for the decline are contentious, habitat degradation and overexploitation appear to be major factors (Rimmer and Russell, 1998b). The primary goal of fish stocking groups in Queensland is to restore depleted barramundi stocks and therefore improve production. In addition, the Queensland Department of Primary Industries has initiated a series of trial stockings of barramundi into the Johnstone River, north Queensland, to assess the efficacy of stock enhancement as a management tool and to evaluate its cost-effectiveness.

Measure of success

Demonstrating improved catches is probably the major performance indicator of most stocking programmes although Cowx (1994) points out that such a stocking exercise still might not be successful if it does not lead to a successful spawning stock or sustained recruitment. Leber, Brennan and Arce (1995) assert that the central issue that needs resolution in marine stock enhancement is the hypothesis that hatchery releases can actually increase population size of the stocked species. They maintain that two important and largely untested predictions underlie this hypothesis. The first is that significant numbers of hatchery fish can survive in the wild and the second is that released hatchery fish actually increase abundances rather than displace wild stocks. We have attempted to test both of these predictions in the trial stocking of barramundi into the Johnstone River in north Queensland.

To test the first prediction that hatchery fish can survive, it was first necessary to be able to discriminate between hatchery fish and wild stocks. Richards and Edwards (1986) believed that the only effective method of assessing the success of a stocking was to mark the fish before release and to monitor the catches. A number of techniques to mark juvenile barramundi were trialled and coded wire tags were found to be the most suitable (Russell and Hales, 1992). Russell and Hales (1992) found that, when

FIGURE 10. CPUE for the recreational barramundi fishery in the Johnstone River between October 1993 and June 1998



implanted into the cheek muscle, coded wire tags had no significant effect on either survival or growth and tag retention was generally > 96 percent and tagging mortality < 1 percent. All fish released in the Johnstone River barramundi stock enhancement experiment were marked with coded wire tags and a monitoring programme implemented that drew samples from commercial, recreational and research catches (Russell and Rimmer, 1997; Rimmer and Russell, 1998b). Stocked fish have entered the fishery and comprise around 20 percent of barramundi from relevant size classes in the research catches (Rimmer and Russell, 1998b), 13 percent in commercial catches and 19 percent in recreational catches. There appears to little likelihood that large-scale dispersal of stocked fish into other river systems will impact on the success of the stocking. Most (62 percent) stocked barramundi were recaptured within 3 km of their release location catches (Rimmer and Russell, 1998b) and only about 1 percent have made coastal or inter-riverine movements.

The second prediction of Leber, Brennan and Arce (1995) confirming that released hatchery fish actually increase abundances rather than displace wild stocks is more problematic. In the Johnstone River study we proposed to test this by determining changes in the CPUE of the recreational fishery using voluntary angler record cards (Russell and Rimmer, 1997; Rimmer and Russell, 1998b). From December 1993 to August 1998 about 2 300 cards were received detailing over 4 700 angler hours of fishing activity. Data were supplied on more than 7 000 fish from over 40 different freshwater, estuarine and marine species.

The data reflected the seasonal nature of the fishery by showing large variation within years with monthly CPUE generally less during the cooler winter months and then peaking before the start of the closed season in November and immediately after the opening of the fishery in February (Figure 10) (Rimmer and Russell, 1998b). There is also considerable variation between years and it is difficult to decipher any increasing trend in CPUE that could be attributable to fish stocking. The variability of the data aside, using angler record cards to collect data on the recreational fishery has a number of inherent difficulties not the least of which is to persuade anglers to fully participate over a long period of time. Our attempts to have recreational anglers participate in the angler record card survey were only partially successful, and we were forced to rely on a liaison officer both to distribute record cards and to assist anglers in completing them.

Assessing the impact of stock enhancement on the commercial fishery was also difficult because of the low numbers of commercial fishers working in the Johnstone River catchment. Although there are five or six commercial barramundi fishers in the Johnstone River catchment, only two or three frequently fished this system, and all regularly fished adjacent rivers. Consequently, commercial catch data were highly variable. Whereas stocked fish are now a significant component of the Johnstone River recreational and commercial fisheries, the question of whether stocking equates to an increase in production is yet to be answered and needs to be further addressed.

Economic analysis (cost/benefit)

Rimmer and Russell (1998b) have undertaken preliminary analyses of the costs and benefits of stocking hatchery-reared barramundi into coastal waterways. The costs of purchasing a similar number of same-sized fingerlings from commercial hatcheries were used to calculate the total value of the stocking. Using the results of a previous study (Russell, 1988) they assumed that barramundi would be caught in the recreational and commercial fisheries in a ratio of around 1:3. They also acknowledged that the value of barramundi to the commercial and recreational sectors would be different. Rutledge *et al.* (1990) estimated that the direct costs incurred by a recreational fisher in northeast Queensland to catch a barramundi was approximately $A50. To a commercial fisher, the average barramundi (5 kg whole weight, with a fillet return of about 50 percent valued at $A10/kg) is worth around $A25. Using these data, Rimmer and Russell (1998b) calculated that less than 1 percent of the total number of fish released would need to be subsequently caught to cover the purchase price of the fingerlings. They emphasize that these analyses are conservative and do not include provisions for indirect economic benefits (Rutledge *et al.*, 1990) or indirect costs. On this basis they concluded that stocking of barramundi is likely to be a cost-effective management technique. Further, more detailed, analyses are needed to quantify additionally the economic benefits of barramundi stock enhancement.

Interactions with natural populations

There is little evidence of any significant interactions between stocked and natural populations of barramundi. They simultaneously occupy the same habitats, they form mixed schools and there is no evidence of any differences in catchability. There is no information on extraordinary interactions with other species. Growth of stocked fish is similar to growth rates documented for natural populations of barramundi in rivers in Papua New Guinea and in the Northern Territory and other parts of Queensland (Davis and Kirkwood, 1984; Rimmer and Russell, 1998b).

ASSOCIATED MANAGEMENT STRATEGIES

In Queensland, a fish stocking permit needs to be issued by the responsible fisheries management agency (QFMA, 1998). In general, authorities to stock public waters are only issued to fish stocking groups comprising members of the local community and to groups that have developed a recognized fish stocking plan (QFMA, 1998). These authorities are issued for periods up to five years for approved stocking plans. Proposals to stock conservation areas such as National Parks, World Heritage Areas and Marine Parks are only considered in consultation with the appropriate managers of those areas. Stocking activities must also be consistent with the translocation policy for non-indigenous genetic stocks, which is outlined in the Genetic resource management section.

In north Queensland, special management provisions were developed to facilitate barramundi fish stocking in the Russell/Mulgrave rivers. All commercial gillnetting for barramundi in those rivers was stopped and a three-year moratorium was placed on the use of cast and seine nets by recreational fishers ostensibly to protect stocked barramundi fingerlings. No information is available on the impact of these measures.

MEASURES TAKEN TO PROTECT AQUATIC BIOLOGICAL DIVERSITY AND OTHER FISHERIES

To date there is no indication that aquatic biological diversity has been affected by stocking barramundi in open systems. However, stocking barramundi in rivers and estuaries is a relatively recent innovation and the numbers stocked are low by world standards (typically thousands or tens of thousands per year per catchment). In Queensland, releases are controlled by a permit system administered by the Queensland Fisheries Management Authority (Cadwallader, 1997). Although barramundi stocking in other Australian states is less widespread than in Queensland, stockings in the Northern Territory and in Western Australia are also controlled by the respective state Fisheries Departments.

There has been considerable debate about the impacts of barramundi stocking, and debate continues, particularly regarding the genetic impacts. Queensland, the Northern Territory and Western Australia have translocation policies that limit or prohibit the interstate importation of barramundi and limit within-state translocation to prevent mixing different genetic strains.

SCOPE FOR ADAPTIVE MANAGEMENT

The results achieved to date from our stock enhancement research readily lend themselves to adaptive management. For example, we have demonstrated that survival of fish stocked at different locations varies substantially, with no survival of fish stocked in one particular location (Rimmer and Russell, 1998b). Optimal stocking sites appear to be those with extensive sublittoral vegetation that provides shelter for juvenile barramundi. One strength of the Queensland stocking system, which relies heavily on the activities of local stocking groups, is that local people have a good knowledge of potential stocking sites, so that better sites can be accessed. This is particularly the case with fishers, who make up most of the membership of these stocking groups, and are familiar with large areas of local waterways and the available habitat.

Our ongoing and future research will include experiments focused on size-at-release, release season and "soft" release strategies. This research is aimed at providing information to be used to develop improved stocking practices, and to improve the cost-efficacy of stocking programmes.

GENERAL CONCLUSIONS

General lessons

Our research has demonstrated that stocked barramundi survive to enter both the recreational and the commercial fisheries. Unfortunately, the generally low but highly variable catch rates that we have found in both the commercial and the recreational sectors have precluded demonstrating that stocked barramundi actually enhance the fishery. This demonstrates the difficulty in showing enhancement in an area with a small population base, and thus a small sample of both recreational and commercial fishers.

We have demonstrated that stocking even small numbers of barramundi (tens of thousands per year) can have a significant impact on local stocks. This has important implications in terms of genetic management of stocking for barramundi. Based on our results, it is relatively easy to produce large numbers of fish from a restricted genetic base and to impact a local population with these fish. It is essential that genetic management strategies for barramundi are developed and implemented rapidly to prevent adverse genetic impacts among stocked populations.

Our cost–benefit analysis has shown that even a modest contribution to the fishery (equivalent to < 1% survival) is cost effective. Although we have been unable to demonstrate that stocked fish enhance catches, such a modest contribution can be regarded as readily achievable.

Strengths and weakness of the programme

An important feature of Queensland's barramundi stocking programme is the active involvement of community stocking groups, which is both a strength and a weakness of the programme. Community involvement in stocking provides greater community ownership of the programme and its outcomes. However, most of the members of these stocking groups have little or no technical knowledge of many of the issues involved in marine stock enhancement.

Management of the genetic resources of stocked barramundi populations remains a major challenge. As noted above, the large size of adult barramundi coupled with the low proportion of fish that breed in captivity means that large hatcheries are necessary to hold the numbers of brood fish necessary to support a marine enhancement programme.

Future prospects and limitations

The barramundi is a highly prized finfish species in northern Australia, and is in demand by both the recreational and the commercial fishery sectors (Rutledge *et al.*, 1990). Stocking barramundi is perceived by the community to be a successful method for enhancing barramundi populations, and there is increasing demand throughout northern Australia for stocking programs to be continued or expanded (Doupé and Bird, 1999).

Limitations to the expansion of stock enhancement of barramundi are largely related to genetic issues and the environmental impacts of stocking large numbers of peak predators in aquatic systems. The policy enacted by most Australian state fisheries authorities that limits stocking of barramundi to the progeny of fish originating from the local genetic strain effectively limits the geographical area where barramundi can be stocked. For example, in Queensland, only three of the six strains found in the wild are represented in hatcheries.

There has also been concern expressed regarding the impact of stocking large numbers of peak predators into aquatic systems, and the impacts that this may have on a range of aquatic species. For example, what density of barramundi represents a "natural" density in the highly impacted catchments where barramundi are usually stocked? This and other questions will need to be addressed before sea ranching for barramundi in Australia is fully accepted as a legitimate and essential component of fisheries management.

References

Allendorf, F.W. & Ryman, N. 1987. Genetic management of hatchery stocks. In N. Ryman & F. Utter, eds. *Population genetics and fishery management*, pp. 141– 159. Seattle, USA, University of Washington Press.

Anderson, I., Barlow, C., Fielder, S., Hallam, D., Heasman, M. & Rimmer, M. 1993. Occurrence of the picorna-like virus infecting barramundi. *Austasia Aquaculture*, 7(2): 42–44.

Anderson, I.G. & Norton, J.H. 1991. Diseases of barramundi in aquaculture. *Austasia Aquaculture*, 5(8): 21–24.

Anderson, T.A., Matthews, S.J., Gamage, K.R., Appleford, P., Garrett, R., Rimmer, M., Hall, M. & Schipp, G. 1998. CRC for aquaculture project – control of reproduction in barramundi. *In* M. J. Wingfield, ed. *Proceedings of the Australian Barramundi Farming Workshop*, pp. 10–17. Cairns, Australia, 30–31 July 1998.

Anon. 1988. Draft management plan released for barramundi. *FINS* 21(3): 28–31.

Anon. 1995. Barramundi *Lates calcarifer. Special series on aquaculture species*, Number 9. Perth, Australia, Fisheries Western Australia.

AQUACOP, Fuchs, J. & Nédélec, G. 1990. Larval rearing and weaning of seabass, *Lates calcarifer* (Block), on experimental compound diets. *In* J. Barret, ed. *Advances in tropical aquaculture*, pp. 677–697. Proceedings of a Workshop, 20 February – 4 March 1989, at Tahiti, French Polynesia. AQUACOP IFREMER Actes de Colloque 9.

Barlow, C.G. 1984. The Nile perch project: progress and plans. *Search*, 15(3–4): 88–91.

Barlow, C.G. & Lisle, A. 1987. Biology of the Nile perch *Lates niloticus* (Pisces: Centropomidae) with reference to its proposed role as a sport fish in Australia. *Biol. Conserv.*, 39: 269–289.

Barlow, C., Williams, K. & Rimmer, M. 1996. Sea bass culture in Australia. *Infofish Int.*, 2(96): 26–33.

Blankenship H.L. & Leber K.M. 1995. A responsible approach to marine stock enhancement. *Am. Fisheries Soc. Symp.*, 15: 167–175.

Cadwallader, P.L. 1995. The need for a responsible approach to fish stocking in Queensland. *In* P. Cadwallader & B. Kirby, eds. *Fish stocking in Queensland – getting it right*, pp. 2–7. Proceedings of Symposium, Townsville, 11 November 1995.

Cadwallader, P. 1997. The decision-making process in relation to the enhancement of catadromous fish stocks in Queensland, Australia. *In First International Symposium on Stock Enhancement and Sea Ranching.* Bergen, Norway, 8–11 September 1997. 88 pp.

Couchman, D., Mayer, D. & Beumer, J. 1996. *Departmental procedures for permit applications assessment and approvals for marine plants.* Queensland Department of Primary Industries. 62 pp.

Cowx, I.G. 1994. Stocking strategies. *Fisheries Manage. Ecol.*, 1: 15–30

Davis, T.L.O. 1982. Maturity and sexuality in barramundi, *Lates calcarifer* (Bloch), in the Northern Territory and south-eastern Gulf of Carpentaria. *Australian J. Marine Freshwater Res.*, 33: 529–545.

Davis, T.L.O. 1984a. A population of sexually precocious barramundi, *Lates calcarifer*, in the Gulf of Carpentaria, Australia. *Copeia* 1: 144–149.

Davis, T.L.O. 1984b. Estimation of fecudity in barramundi, *Lates calcarifer* (Bloch), using an automatic particle counter. Australian J. Marine Freshwater Res., 35: 111–118.

Davis, T.L.O. 1985a. Seasonal changes in gonad maturity, and abundance of larvae and early juveniles of barramundi, *Lates calcarifer* (Bloch) in Van Dieman Gulf and the Gulf of Carpentaria. *Australian J. Marine Freshwater Res.*, 36: 177–190.

Davis, T.L.O. 1985b. The food of barramundi, *Lates calcarifer* (Bloch), in coastal and inland waters of Van Diemen Gulf and the Gulf of Carpentaria, *Australia. J. Fish Biol.*, 26: 669–682.

Davis, T.L.O. 1986. Migration patterns in barramundi, *Lates calcarifer* (Bloch), in van Diemen Gulf, Australia with estimates of fishing mortality in specific areas. *Fisheries Res.*, 4: 243–258.

Davis, T.L.O. & Kirkwood G.P. 1984. Age and growth studies on barramundi, Lates calcarifer (Bloch) in northern Australia. *Australian J. Marine Freshwater Res.*, 35: 673–690.

Department of Primary Industry and Fisheries. 1991. *Northern Territory Barramundi Fishery Management Plan.* Fisheries Division. 85 pp.

Dunstan, D.J. 1959. *The barramundi Lates calcarifer (Bloch) in Queensland waters.* CSIRO Division of Fisheries and Oceanography, Technical Paper Number 5. 22 pp.

Dhert, P., Lavens, P., Duray, M. & Sorgeloos, P. 1990. Improved larval survival at metamorphosis of Asian seabass (*Lates calcarifer*) using 3-HUFA-enriched live food. *Aquaculture* 90: 63–74.

Doupé, R. 1997. Getting a grip on Kimberley barra. *Western Fisheries*, 21–25.

Doupé, R.G. & Bird, C. 1999. Opportunities for enhancing the recreational fishery of Lake Kununurra using barramundi *Lates calcarifer*: a review. *Proc. Royal Soc. Queensland*, 108: 41–48.

Fallu, R. 1996. *Barramundi – status report 1996.* Northern Territory Department of Primary Industry and Fisheries.

FAO. 1984. *Manual for spawning of seabass, Lates calcarifer, in captivity*, by **T.** Tattanon & B. Tiensongrusmee. Rome, FAO. 22 pp.

Garrett, R.N. 1987. Reproduction in Queensland barramundi (*Lates calcarifer*). *In* J. W. Copland & D. L. Grey, eds.*Management of wild and cultured sea bass / barramundi (Lates calcarifer)*, pp. 38–43. Proceedings of an International Workshop held at Darwin, N.T., Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

Garrett, R.N. & Connell, M.R.J. 1991. Induced breeding in barramundi. *Austasia Aquaculture* 5(8): 10–12.

Garrett, R.N. & O'Brien, J.J. 1993. All-year-around spawning of hatchery barramundi in Australia. *Austasia Aquaculture*, 8(2): 40–42.

Geiger, J.G. 1983a. Zooplankton production and manipulation in striped bass rearing ponds. *Aquaculture*, 35: 331–351.

Geiger, J.G. 1983b. A review of pond zooplankton production and fertilization for the culture of larval and fingerling striped bass. *Aquaculture*, 35: 353–369.

Glazebrook, J.S. & Heasman, M.P. 1992. Diagnosis and control of picorna-like virus infections in larval barramundi, *Lates calcarifer* Bloch. *In* M. Shariff, R. P. Subasinghe and J. R. Arthur, eds. *Diseases in Asian aquaculture I*, pp. 267–272. Manila, Fish Health Section, Asian Fisheries Society.

Glazebrook, J.S., Heasman, M.P. & de Beer, S.W. 1990. Picorna-like viral particles associated with mass mortalities in larval barramundi, *Lates calcarifer* (Bloch). *J. Fish Diseases*, 13: 245–249.

Greenwood, P.H. 1976. A review of the family Centropomidae (Pisces: Perciformes). *Bull. Br. Museum (Natural History) Zool.*, 29: 4–81.

Grey, D.L. 1986. The development and management of the Northern Territory barramundi (*Lates calcarifer*) fishery. *In* J. L. McLean, L. B. Dizon & L.V. Hosillos, eds. *Proceedings of the First Asian Fisheries Forum*, pp. 375–380. Manilla, Asian Fisheries Society.

Grey, D.L. 1987. An overview of *Lates calcarifer* in Australia and Asia. *In* J. W. Copland & D. L. Grey eds. *Management of wild and cultured sea bass/barramundi (Lates calcarifer)*, pp. 15–21. Proceedings of an International Workshop held at Darwin, Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

Griffin, R.K. 1986. The importance of mangrove/coastal wetland to three commercial fisheries in the Northern Territory; particularly for barramundi (*Lates calcarifer*). *In* K. N. Bardsley, J. D. S. Davie & C. D. Woodroffe, eds. *Proceedings of a conference on coastal tidal wetlands of Australian monsoon region*, pp. 277–283. Darwin, Australia, Northern Australian Research Unit, Australian National University.

Griffin, R.K. 1987. Life history, distribution and seasonal migration of barramundi, *Lates calcarifer* (Bloch) in the Daly River, Northern Territory, Australia. *In* M. J. Dadswell, R. J. Klauda, C. M. Moffitt & R. L. Saunders, eds. *Proceedings of an international symposium on common strategies of anadromous and catadromous fishes*, pp 358–363. Boston, USA, American Fisheries Society Symposium No. 1.

Griffin, R.K. 1993. The recreational fishery for barramundi, (*Lates calcarifer*) in the Mary River, Northern Territory, 1986–1992. *Fishery report* Number 30. Department of Primary Industry and Fisheries, Northern Territory. 16 pp.

Kailola, P.J., Williams, M.J., Stewart, P.C., Reichelt, R.E., McNee, A. & Grieve, C. 1993. *Australian Fisheries Resources*. Bureau of Resource Sciences and the Fisheries Research and Development Corporation.

Keenan, C.P. 1994. Recent evolution of population structure in Australian barramundi, *Lates calcarifer* (Bloch): an example of isolation by distance in one dimension. *Australian J. Marine Freshwater Res.*, 45: 1123–1148.

Kohno, H., Hara, S. & Taki, Y. 1986. Early larval development of the seabass *Lates calcarifer* with emphasis on the transition of energy sources. *Bull. Japan. Soc. Sci. Fisheries*, 52: 1719–1725.

Lea, R., Grey, D. & Griffin, R. 1987. Utilisation and wildstock management of barramundi (*Lates calcarifer*) in the Northern Territory. In J. W. Copland & D. L. Grey, eds. *Management of wild and cultured sea bass/barramundi (Lates calcarifer)*, pp. 82–86. Proceedings of an International Workshop held at Darwin, Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

Leber, K.M., Brennan, N.P. & Arce, S.M. 1995. Marine enhancement with striped mullet: are hatchery releases replenishing or displacing wild stocks? *Am. Fisheries Soc. Symp.*, 15: 376–387.

Lobegeiger, R. 1993. Economic benefits of the extensive rearing system for barramundi larvae. *Queensland Aquaculture News*, Issue 2 (July, 1993): 7 pp.

Lobegeiger, R. 1999. *Report to Farmers: Aquaculture Production Survey Queensland 1997–98.* Queensland Department of Primary Industries Information Series QI99017. 24 pp.

Ludescher, C.M. 1997. *Fisheries resources between Bowen and Tully – an inventory.* Queensland Fisheries Management Authority. 136 pp.

MacKinnon, M.R. 1987. Rearing and growth of larval and juvenile barramundi (*Lates calcarifer*) in Queensland. *In* J. W. Copland & D. L. Grey eds. *Management of wild and cultured sea bass/barramundi (Lates calcarifer)*, pp. 148– 153. Proceedings of an International Workshop held at Darwin, Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

MacKinnon, M.R. 1990. Status and potential of Australian *Lates calcalifer* culture. *In* J. Barret, ed. *Advances in tropical aquaculture*, pp. 713–727. Proceedings of a Workshop, 20 February – 4 March 1989, at Tahiti, French Polynesia. AQUACOP IFREMER Actes de Colloques 9.

MacKinnon, M.R. & Cooper, P.R. 1987. Reservoir stocking of barramundi for enhancement of the recreational fishery. *Australian Fisheries*, 46(7): 34–37.

Midgely, S.H. 1968. *A study of Nile perch in Africa (and consideration as to its suitably for Australian tropical inland waters).* Winston Churchill Memorial Trust Fellowship Report No. 3.

Milton, D.A., Die, D., Tenakanai, C. & Swales, S. 1998. Selectivity for barramundi (*Lates calcarifer*) in the Fly River, Papua New Guinea: implications for managing gill-net fisheries on protandrous fishes. *Mar. Freshwater Res.*, 49: 499–506.

Moore, R. 1979. Natural sex inversion in the giant perch (*Lates calcarifer*). *Australian J. Marine Freshwater Res.*, 30: 803–813.

Moore, R. 1980. *Reproduction and migration in Lates calcarifer* (Bloch). University of London. 213 pp. (Ph.D. thesis)

Moore, R. 1982. Spawning and early life history of barramundi *Lates calcarifer* in Papua New Guinea. *Australian J. Marine Freshwater Res.*, 33: 647–661.

Moore, R. & Reynolds, L.F. 1982. Migration patterns of Barramundi, *Lates calcarifer* in Papua New Guinea. *Australian J. Marine Freshwater Res.*, 33: 671–682.

Munday, B.L., Langdon, J.S., Hyatt, A. & Humphrey, J.D. 1992. Mass mortality associated with a viral-induced vacuolating encephalopathy and retinopathy of larval and juvenile barramundi, *Lates calcarifer* Bloch. *Aquaculture*, 103: 197–211.

NICA. 1986. *Technical manual for seed production of seabass.* Songkhla, Thailand, National Institute of Coastal Aquaculture. 49 pp.

Palmer, P.J., Burke, J.B., Willett, D.J. & Simpson, R.R. 1992. *Development of a low-maintenance technique for rearing barramundi (Bloch) larvae.* Queensland Department of Primary Industries Information Series QI92036. 19 pp.

Parazo, M.M., Garcia, L.Ma.B., Ayson, F.G., Fermin, A.C., Almendras, J.M.E., Reyes, D.M. Jr & Avila, E.M. 1990. *Sea bass hatchery operations.* Aquaculture Extension Manual No. 18, Aquaculture Department, Southeast Asian Fisheries Development Center. 38 pp.

Pearson, R.G. 1987. Barramundi breeding research - laying the foundations for industry. *Australian Fisheries*, 46(7): 2–3.

Pender, P. 1995. Northern Territory Barramundi fishery – management decisions taken for reasons of biological and non biological necessity. *In* F. Prokop, ed. *The best available information – its implications for recreational fisheries management.* Western Australian Fisheries Management Paper No. 87: 86–90.

Pender, P.J. & Griffin, R.K. 1996. Habitat history of Barramundi *Lates calcarifer* in a north Australian river system based on barium and strontium levels in scales. *Trans. Am. Fisheries Soc.*, 125: 679–689.

QFMA. 1996. *Queensland Gulf of Carpentaria Inshore Finfish Fishery*. Discussion Paper Number 1, Queensland Fisheries Management Authority. 42 pp.

QFMA. 1998. *Queensland Freshwater Fisheries – Draft Management Plan and Regulatory Impact Statement*. Queensland Fisheries Management Authority. 100 pp.

QFMA. 1999. *Overview of the Fisheries (Freshwater) Management Plan 1999*. Queensland Fisheries Management Authority. 15 pp.

Quinn, R.H. 1987. Analysis of fisheries logbook information from the Gulf of Carpentaria, Australia. *In* J.W. Copland and D. L. Grey, eds. *Management of wild and cultured sea bass/barramundi (Lates calcarifer)*, pp. 92–95. Proceedings of an International Workshop held at Darwin, Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

Rasmussen, I.R. 1991. Optimum acclimation rates from salt – to freshwater for juvenile sea bass *Lates calcarifer* Bloch. *Asian Fisheries Sci.*, 4: 109–113.

Renault, T., Haffner, P., Baudin Laurencin, F., Breuil, G. & Bonami, J.R. 1991. Mass mortalities in hatchery-reared sea bass (*Lates calcarifer*) larvae associated with the presence in the brain and retina of virus-like particles. *Bull. Eur. Assoc. Fish Pathol.*, 11: 68–73.

Reynolds, L.F. & Moore, R. 1982. Growth rates of barramundi *Lates calcarifer* in Papua New Guinea. *Australian J. Marine Freshwater Res.*, 33: 663–670.

Richards, W.J. & Edwards R.E. 1986 Stocking to restore or enhance marine fisheries. *In* R. H. Stround, ed. *Fish culture in management*, pp.75–80. Bethesda, USA, American Fisheries Society.

Rimmer, M. 1995a. Applying World's best practice to fish stocking programs in Queensland. *In* P. Cadwallader & B. Kerby, eds. *Fish stocking in Queensland – getting it right*, pp. 82–89. Proceedings of the Symposium held in Townsville, Queensland, 11 November 1995. Brisbane, Australia, Queensland Fisheries Management Authority.

Rimmer, M.A. 1995b. *Barramundi farming – an introduction*. Queensland Department of Primary Industries Information Series, QI95020. 26 pp.

Rimmer, M.A., Reed, A.W., Levitt, M.S. & Lisle, A.T. 1994. Effects of nutritional enhancement of live food organisms on growth and survival of barramundi, *Lates calcarifer* (Bloch), larvae. *Aquaculture Fisheries Manage.*, 25: 143–156.

Rimmer, M.A. & Russell, D.J. 1998a. Aspects of the biology and culture of *Lates calcarifer*. *In* S. De Silva, ed. *Tropical mariculture*, pp. 449–476. London, Academic Press.

Rimmer, M.A. & Russell, D.J. 1998b. Survival of stocked barramundi, *Lates calcarifer*, in a coastal river system in far northern Queensland, Australia. *Bull. Mar. Sci.*, 62(2): 325–336.

Rimmer, M.A. & Rutledge, W. 1991. *Extensive rearing of barramundi larvae*. QI91012. Queensland Department of Primary Industries Information Series.

Rodgers, L.J. & Barlow, C.G. 1987. Better nutrition enhances survival of barramundi larvae. *Australian Fisheries*, 46(7): 30–32.

Ruangpanit, N. 1987. Developing hatchery techniques for sea bass (*Lates calcarifer*): a review. *In* J. W. Copland & D. L. Grey, eds. *Management of wild and cultured seabass/barramundi (Lates calcarifer)*, pp. 132–135. Proceedings of an International Workshop, Darwin, Australia. Australian Centre for International Agricultural Research, Proceedings Number 20.

Russell D.J. 1987. Review of juvenile barramundi (*Lates calcarifer*) wildstocks in Australia. *In* J. W. Copland & D. L. Grey, eds. *Management of wild and cultured seabass/barramundi (Lates calcarifer)*, pp. 44–49. Proceedings of an International Workshop, Darwin, Australia. Australian Centre for International Agricultural Research, Proceedings Number 20.

Russell, D.J. 1988. *An assessment of the east Queensland inshore gillnet fishery.* Report Number QI88024. Brisbane, Australia, Queensland Department of Primary Industries. 57 pp.

Russell, D.J. & Garrett, R.N. 1983. Use by juvenile Barramundi Lates calcarifer and other fishes of temporary supralittoral habitats in a tropical estuary in northern Australia. *Australian J. Mar. Freshwater Res.*, 34: 805–811.

Russell, D.J. & Garrett, R.N. 1985. Early life history of Barramundi *Lates calcarifer* in north-eastern Queensland. *Australian J. Mar. Freshwater Res.*, 36: 191–201

Russell, D.J. & Hales, P.W. 1992 Evaluation of techniques for marking juvenile barramundi *Lates calcarifer* (Bloch), for stocking. *Aquaculture and Fisheries Manage.*, 23: 691–699.

Russell, D.J. & Hales, P.W. 1993. *Stream habitat and fisheries resources of the Johnstone River Catchment.* Report No. QI93056. QI96008. Brisbane, Australia, Queensland Department of Primary Industries. 59 pp.

Russell, D.J., Hales, P.W. & Helmke, S.A. 1996a. *Stream habitat and fish resources in the Russell and Mulgrave Rivers Catchment.* QI96008 Brisbane, Australia, Queensland Department of Primary Industries. 52 pp.

Russell, D.J., Hales, P.W. & Helmke, S.A. 1996b. *Fish resources and stream habitat of the Moresby River Catchment.* QI96061. Brisbane, Australia, Queensland Department of Primary Industries. 50 pp.

Russell, D.J. & Rimmer, M.A. 1997. Assessment of stock enhancement of barramundi, *Lates calcarifer* (Bloch) in a coastal river system in far north Queensland, Australia. *In* D. A. Hancock, D. C. Smith & J. P. Beumer, eds. *Developing and sustaining world fisheries resources – the state of science and management*, pp. 498–503. Proceedings of 2nd World Fisheries Congress, 28 July – 2 August, 1996, Brisbane, Queensland.

Rutledge, W.P. & Rimmer, M.A. 1991. Culture of larval sea bass, *Lates calcarifer* (Bloch), in saltwater rearing ponds in Queensland, Australia. *Asian Fisheries Sci.*, 4: 345–355.

Rutledge, W.P., Rimmer, M., Russell, D., Garrett, R. & Barlow, C. 1990. Cost benefit of hatchery-reared barramundi, *Lates calcarifer* (Bloch), in Queensland. *Aquaculture and Fisheries Manage.*, 21: 443–448.

Salini, J.P. & Shaklee, J.B. 1988. Genetic structure of barramundi (*Lates calcarifer*) stocks from northern Australia. *Australian J. Mar. Freshwater Res.*, 39: 317–329

Shaklee, J.B. & Salini, J.P. 1985. Genetic variation and population subdivision in Australian barramundi, *Lates calcarifer* (Bloch). *Australian J. Mar. Freshwater Res.*, 36: 203–218.

Shaklee , J.B., Salini, J.P. & Garrett, R.N. 1993. Electrophoretic characterisation of multiple genetic stocks of barramundi perch in Queensland, Australia. *Trans. Am. Fisheries Soc.*, 122:685–701.

Tait, J. 1995. Habitat rehabilitation – looking beyond the easy fix for natural fish stocks. *In* P. Cadwallader & B. Kirby, eds. *Fish stocking in Queensland – getting it right*, pp. 41–50. Proceedings of Symposium, Townsville, 11 November 1995.

Tringali, M.D. & Bert, T.M. 1998. Risk to genetic effective population size should be an important consideration in fish stock-enhancement programs. *Bull. Mar. Sci.* 62: 641–659.

Williams, L.E., ed. 1997. *Queensland's fisheries resources – current condition and recent trends 1988–1995*. Brisbane, Australia, Queensland Department of Primary Industries. 101 pp.

Appendix 1

TRANSLOCATION PRINCIPLES

Principles for translocation of fishes in Queensland as listed in QFMA (1999)

The following translocation policy principles have been adopted by the QFMA to ensure that the stocking of fish into public and private waters for recreation, conservation or, where appropriate, other purposes is in accordance with the principles of ecologically sustainable development, including the maintenance of ecological systems and the protection of biodiversity, and dealing cautiously with risk, uncertainty and irreversibility (the Precautionary Principle).

- Stocking public or private waters with translocated species or non-indigenous genetic stocks of a species will be considered only where a clear economic, social or conservation benefit can be demonstrated, and where no alternative native species in the drainage basin has similar potential.
- Translocation will not be permitted in catchments where the integrity of native fish communities remains substantially intact and/or there are one or more threatened species of fish or other aquatic organisms (conservation priority catchments) and/or there are several native fish species of value (translocation unnecessary catchments)
- Translocation of species accorded threatened status because of habitat loss or other factors will be supported. Here, the emphasis is on the establishment of breeding populations (to be carried out in accordance with the principles of the draft Australian and New Zealand Environment and Conservation Council policy for the translocation of vertebrate animals in Australia).
- With the exception of threatened species, preference will be given for translocating species, which will not form self-sustaining populations in their target environment.
- Where a basin or river system is contiguous with another State, the agreement of that State must be obtained before any translocation can take place. Queensland will seek reciprocal agreements with other States.
- All potential translocations will be subject to disease risk assessments to minimize the risk of disease transfers.
- All proposals to translocate fish species or non-indigenous stocks of the same species are to be considered on a case-by-case basis according to a decision-making protocol and standard procedures.

The QFMA and the Department of Primary Industries, Fisheries Group have recognized that translocations must be strictly controlled if irreversible damage to native fish communities is to be avoided. It is recognized that a number of translocations have occurred in the initial 10 years of the Government's recreational Freshwater Fishing Enhancement Programme and that these have created valuable recreational fisheries. These are allowed to continue, but new translocations will be considered only if there is very good evidence that the risks are minimal. Preference will be given to species that will not reproduce in their new environment, as such translocations are reversible.

This approach has been developed by the QFMA and the DPI in consultation with fish stocking associations. It allows for the responsible development of Queensland's recreational freshwater fisheries without threatening the State's wild fisheries.

The restocking of sea cucumbers in the Pacific Islands[1]

Stephen C. Battaglene
University of Tasmania, Tasmanian Aquaculture
and Fisheries Institute, Marine Research Laboratories,
Nubeena Crescent, Taroona, Tasmania, 7053, Australia

Johann D. Bell
WorldFish Center,
PO Box 500 GPO, 10670 Penang, Malaysia
WorldFish Center

Large invertebrates associated with coral reefs are an important source of food and income for coastal communities in the small island developing states (SIDS) of the Pacific (Wright and Hill, 1993; Richards, Bell and Bell, 1994; Dalzell, Adams and Polunin, 1996). Although the volume of these fisheries is low by world standards, they are of considerable economic importance to SIDS because the ratio of coastline to landmass is much greater than for continental countries (Adams, 1998). It is now evident, however, that the inshore invertebrate fisheries are not yielding their full potential. This is not due to lack of development. Rather, the problems facing these fisheries have been caused by overharvesting, with the result that in many places there are too few adults to replenish stocks regularly. In short, the natural supply of juveniles is often well below the carrying capacity of the coral reef habitats.

Part of the solution to the current lack of productivity from coral reefs in the Pacific is to raise awareness of the need to allow stocks to recover to productive levels, and to implement community-based management (Lam, 1998). However, improved awareness and protection will not necessarily result in rapid recovery of stocks, and will not deliver increased levels of production compared with historical catches. Both these outcomes are essential for the increased well-being of the rapidly growing human populations in the Pacific.

Aquaculture, in a variety of forms, is needed to redress the problem of low yields from inshore invertebrate fisheries in the Pacific (Bell, 1999a). Aquaculture can be used to increase productivity in three ways. First, cultured juveniles can be released into the wild to restore stocks to levels at which they provide substantial, sustainable yields. This process is known as "restocking".

Second, cultured juveniles can be released into the wild to increase stocks compared with historical, unexploited levels. This process is known as "stock enhancement" and is designed to overcome the common phenomenon of "recruitment limitation"

---

[1] Since this manuscript was submitted for publication in 2001, considerable progress has been made on methods for hatchery production of sandfish (*Holothuria scabra*), the techniques for releasing the cultured juveniles in the wild, and the ways to assess the potential benefit of restocking programmes to the sustainable management of fisheries for sea cucumbers. This progress has been documented in the recent publication by FAO entitled "Advances in sea cucumber aquaculture and management" A. Lovatelli, C. Conand, S. Purcell, S. Uthicke, J.-F. Hamel and A. Mercier (Eds.). FAO Fisheries Technical Paper 463, FAO, Rome, 2004, 425pp.

(Doherty, 1999). This phenomenon occurs when the natural supply of juveniles fails to reach the carrying capacity of the habitat, even when there are great numbers of breeding adults. Recruitment limitation is the rule rather than the exception among tropical marine animals and arises for several reasons. For example, the floating (pelagic) larval stages of fish and shellfish may perish en masse in the plankton because of lack of suitable food, or be swept away from coral reefs by currents, thus preventing successful settlement. Mass mortality of larvae as a result of predation can also occur when they cease their pelagic phase and settle on coral reefs. The result of recruitment limitation is that (even unexploited) coral reef habitats do not produce as many valuable shellfish as they could. Stock enhancement seeks to redress this situation by supplying as many juveniles as the habitat can support (Munro and Bell, 1997; Doherty, 1999). Stock enhancement and restocking are not without pitfalls, however, and the factors that need to be considered for responsible implementation of such programmes, and transferring the technology to the Pacific, are described by Blankenship and Leber (1995), Munro and Bell (1997) and Bell (1999b).

Third, cultured juveniles can be grown in captivity to increase productivity independently from the management of wild fisheries. This process is usually referred to as "aquaculture" or "farming".

The imperative for SIDS in the Pacific is to apply aquaculture technology to the restocking of several invertebrate fisheries, and then to introduce sound management of the resources, so that increased yields can be made sustainably in the near future. In time, the same technology can also be used in stock enhancement programmes to ensure that maximum yields are obtained by overcoming recruitment limitation.

Although the way forward for SIDS is clear, they usually do not have the financial and human resources to develop the technology for restocking marine species. Instead, they need to rely on international and regional organizations to do this work on their behalf. They will also need to rely on donors to implement restocking programmes until the additional revenue from the increased catches can be levied to meet the cost of further restocking, or stock enhancement (Bell, 1999b).

The WorldFish Center, in collaboration with several partners, has begun the development of technology for restocking valuable coral reef invertebrates on behalf of Pacific Islands (see Lawrence, 1999, for details). To date, the research has focused on developing methods for the restocking of giant clams (Tridacnidae),trochus or topshell (*Trochus niloticus*) and sea cucumbers (Holothuroidea). The technology for propagating and restocking giant clams is now documented and widely available (see Munro, 1993a, 1993b; Lucas, 1994; Mungoa-Licuanan and Gomez,1996 and Bell, 1999c, for reviews), and the status of restocking programmes has been reviewed by Bell (1999c). The efforts to restock trochus through release of hatchery-reared juveniles are still at an early stage (Nash, 1993; Lee *et al.*, 1998), although adults have been introduced to more than 50 locations in the Pacific to create fisheries (Eldredge, 1994).

In this paper, we expand on our previous report (Battaglene and Bell, 1999) on the potential of tropical sea cucumbers for stock enhancement and focus on the need for, and progress of, methods for restocking sea cucumbers in the Pacific. We describe the fishery for bêche-de-mer (processed sea cucumbers), outline the rationale for restocking sea cucumbers, summarize the methods that have been developed and identify the work that remains to be done before responsible restocking methods will be available for dissemination to SIDS in the Pacific. Much of the research we refer to has been done in the Solomon Islands, but it can also be applied to any other SIDS in the region and Southeast Asia.

NATURE AND STATUS OF THE FISHERY FOR BÊCHE-DE-MER IN THE PACIFIC

The trade in bêche-de-mer (processed sea cucumbers) is one of the oldest and most widespread forms of commerce in the Pacific Islands (Conand and Byrne, 1993; Holland, 1994a). It is based on the demand for sea cucumbers in Asia, especially mainland China, where the boiled and dried body wall is prized for its aphrodisiac, curative and medicinal properties (Preston, 1993). The body and/or viscera of sea cucumbers are also eaten in Japan, the Republic of Korea and some Pacific Islands (Shelley, 1985; Yanagisawa, 1996), and variously used as food for livestock, production of fish poisons and antifungal agents (Preston, 1993). Although more than 1400 species of sea cucumbers have been described, trade is restricted to the 20–30 species that generally have thick body walls. Most of these species are found in the tropics (Conand and Byrne, 1993; Holland, 1994b; Rowe and Gates, 1995).

Fishing for bêche-de-mer has brought considerable benefits to SIDS in the Pacific because harvesting, processing and storage of sea cucumbers is easy and requires no specialized equipment or refrigeration (Preston, 1993). In several of these countries, bêche-de-mer provides the majority of revenue from non-finfish marine resources (e.g. Solomon Islands; Richards, Bell and Bell, 1994) and, for many coastal communities, it is one of the few sources of income. A striking example of the importance of sea cucumbers to Pacific Islands comes from the large, remote atoll of Ontong Java in the Solomon Islands. There, bêche-de-mer has been the major fishery and has provided the majority of cash income for the population (Holland, 1994a).

Other important features of the bêche-de-mer fishery in the Pacific Islands are that it causes little damage to the environment, and does not conflict with the subsistence food requirements of villagers (Holland, 1994b; Dalzell, Adams and Polunin, 1996).

Despite the importance of bêche-de-mer to coastal communities in the Pacific, production remained at low levels for much of this century as a result of previous overfishing, a trade embargo into China caused by the Sino-Japanese war, and later by trade restrictions from the Chinese communist government (Dalzell, Adams and Polunin, 1996). However, the re-entry of China into world trade during the 1980s resulted in a sharp increase in demand and supply of sea cucumbers (Conand and Byrne, 1993; Dalzell, Adams and Polunin, 1996; Conand, 1997). Prices for bêche-de-mer remained strong throughout this period because demand for bêche-de-mer is considered to be highly inelastic, or "insatiable" (Dalzell, Adams and Polunin, 1996). The ability of villagers and wholesalers to store bêche-de-mer for long periods also contributes to stability in the market, and has resulted in bartering of the product to circumvent trade barriers (Dalzell, Adams and Polunin, 1996).

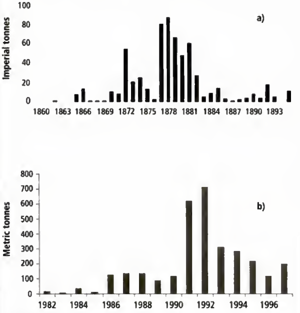
Total imports of bêche-de-mer into Hong Kong, Singapore and Taiwan Province of China from all sources were estimated to be 12 000 tonnes in 1994, valued at US$60 million (Conand and Byrne, 1993; Conand, 1997). Because of shrinkage during processing, 12 000 tonnes of bêche-de-mer represent a wet weight of ~120 000 tonnes. Despite the large volume of bêche-de-mer traded each year, accurate information on the species exploited, the tonnages harvested and the total value of bêche-de-mer exports from SIDS and other developing countries is difficult to obtain (Preston, 1993; Conand and Byrne, 1993). This is because catches are often poorly recorded, and because sea cucumbers can be difficult to identify to species level once processed into bêche-de-mer.

PRINCIPAL PROBLEMS WITH THE FISHERY

The major problem with the bêche-de-mer fishery in the Pacific is that it has followed a "boom and bust" cycle (Preston, 1993). In many places, the initial phase of exploitation reduced the resource to the point at which there was little capacity for replenishment. Indeed, it often took 3–4 decades before stocks of sea cucumbers recovered to levels at which profitable harvests were again possible. The long time frames needed for recovery of bêche-de-mer fisheries are related to the fact that sea cucumbers can be harvested to very low levels, and that there is often limited scope for replenishment from the nearest source of spawners as a result of the large distances and the relatively short larvaafter Bennetl cycles. The boom and bust cycle has been repeated several times in some countries although, as mentioned previously, a trade embargo provided an extended period for recovery at one stage.

The fishery in the Solomon Islands provides a typical example of the long-term, cyclical nature of the bêche-de-mer industry. The historical records of bêche-de-mer exports from 1860 to 1895 provided by Bennett (1987) indicate a pulse of fishing that peaked in 1878 followed by rapid depletion of the resource (Figure 1a). Production of bêche-de-mer then remained at low levels for much of the twentieth century, in part owing to the disruptions of the Second World War. Fishing recommenced in earnest in the mid 1980s, with catches peaking in 1992 at 716 tonnes and then declining rapidly

FIGURE 1. Export of beche-de mer from the Solomon Islands from: a) 1854 to 1896 (after Bennett, 1987), and b) 1982 to 1997 (data from the Solomon Island Department of Fisheries and Marine Resources

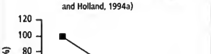


to 120 tonnes by 1996 (Figure b). A slight recovery in 1997 reflected the opening of waters off Bouganville on the western border of the Solomon Islands.

Richmond (1997) refers to a case of complete overexploitation of sea cucumbers from a relatively isolated location in the Pacific, where there was no recovery 50 years after intense harvesting. He reports that thousands of tonnes of commercially valuable sea cucumbers were exported from Chuuk (Truk) to Japan in the late 1930s, but that surveys in 1988 found only two individuals of one edible species. His interviews with local residents and fishermen confirmed that there have been no harvests of sea cucumbers in the intervening period.

The problems facing the bêche-de-mer fishery during the recent "boom" in the cycle were driven by the high prices being paid for valuable species, and the fact that coastal communities in SIDS often have few other options to derive income. Four general trends have emerged during the most recent harvesting cycle. First, high-value species have been fished heavily (Conand and Byrne, 1993; Dalzell, Adams and Polunin, 1996). The average wholesale price for these species is now around US$50/ kg, although price is highly variable depending on quality: premium prices are paid for large animals and the price for smaller specimens declines rapidly (Figure 2). The value of first-grade, i.e. large and well-processed, bêche-de-mer has more than doubled since 1993 (Conand, 1997). Second, the species composition of exports has changed: catches of high-value species are lower and more species are being exploited. The relatively low catch of high-value species has been particularly evident in the Solomon Islands and Fiji (Holland, 1994a; Dalzell, Adams and Polunin, 1996). Third, the mean size of many harvested species has declined (Dalzell, 1990; Holland, 1994b). Fourth, there has been a tendency for the development of centralized processing facilities that reduce the economic benefits to coastal villages and lead to localized resource depletion (Adams, 1992; Preston, 1993). Together, these four trends indicate that stocks of tropical sea cucumbers have once again been overfished.

FIGURE 2. Percentage change in prices paid for beche-de-mer (sandfish) of different sizes (data from exporters in Singapore and Holland, 1994a)



CURRENT MANAGEMENT PRACTICES

The premium prices paid for large specimens mean that sea cucumber fisheries need to be managed in a way that maximizes the economic return per recruit through regulations that provide for sustainable harvests comprising large individuals. However, it has not been easy to establish the scientific basis for such management. In particular, the large number of species of sea cucumbers now being targeted, and the remote and artisanal nature of fisheries for bêche-de-mer, make it expensive to collect the data on catch-per-unit-effort, growth and mortality that are normally used to manage marine fisheries on a sustainable basis (Shelley, 1985; Conand and Byrne, 1993; Lokani, 1995). Consequently, the only data on species composition and size frequency of wild stocks in many countries are those provided by exporters (Adams, 1992; Holland, 1994a; Lokani, 1995).

Even if it was possible for SIDS to obtain the resources needed to collect the necessary data, the length and weight of sea cucumbers are not easy to measure: individuals retain water and sediment to varying degrees. Modal progressions in growth are also difficult to interpret because many sea cucumbers are capable of asexual reproduction by binary fission, and evisceration and shrinkage when stressed (Preston, 1993; Reichenbach, Nishar and Saeed, 1996). In addition, there are no established tagging methods or ageing techniques for sea cucumbers (Preston, 1993).

One country (the Kingdom of Tonga) has overcome many of the difficulties involved in managing the restoration of an ongoing fishery simply by implementing a long-term prohibition on the export of bêche-de-mer to allow recovery of stocks to productive levels. In most other places in the Pacific, however, management, or recommendations for management, of the bêche-de-mer fishery have been based on scant knowledge of the size at sexual maturity for the numerous species, and measures aimed broadly at preventing "recruitment" and "growth" overfishing (Adams, 1992; Holland, 1994a, 1994b; Lokani, 1995). These measures include size limits, prohibition on collection using compressed air and the use of closed seasons and marine protected areas.

The management measures referred to above have been of limited success. The fact that small bêche-de-mer fetch drastically reduced prices should mitigate against the need for size limits, but this has not been the case (Shelley, 1988; Adams, 1992; Holland, 1994b). Unfortunately, recommendations regarding the need for size limits have not always been adopted by fisheries departments, or those with responsibility for stocks under customary marine tenure arrangements. Rather, fishers have often preferred to catch sea cucumbers at a small size to obtain some cash now instead of waiting to maximize returns. Restrictions on the use of scuba are common and were designed to ensure that sea cucumbers have sanctuary in deeper water so that they can maintain effective breeding populations (Adams, 1992). However, deep-water sanctuaries are of limited benefit to species inhabiting shallow water (<20 m), or in areas of very clear water where free divers have devised methods for collecting at depths >30 m (Holland, 1994a). Closed seasons appear to be working well only in areas with strong traditions and customs. There is little doubt that marine reserves could provide sanctuary for breeding populations, and a source of recruits for nearby areas that remain open to fishing. The major question here, however, is the time required for recovery of stocks. he monitoring of a Marine Conservation Area of 83 km^2 at the Arnavon Islands, Solomon islands, which was dedicated to protect large invertebrates, indicates that replenishment of sea cucumbers is likely to take more than ten years (Lincoln Smith *et al.*, 2000).

An all-encompassing problem, however, is that SIDS often lack the financial and human resources to enforce management regulations. The diverse social and coastal tenure systems of many Pacific Islands also complicate the application of regulations (Conand and Sloan, 1989; Lokani, 1995; Aswani, 1997).

RATIONALE FOR RESTOCKING

Even if SIDS can implement sound management practices for sea cucumber stocks, there are two reasons why the measures described above are unlikely to result in highly productive bêche-de-mer fisheries in the near future. These two reasons have been mentioned in the preceding sections: they are the long timeframes required for restoration of depleted fisheries, and recruitment limitation of restored fisheries.

There is now general recognition that the fastest way to restore the productivity of severely depleted sea cucumber fisheries for the benefit of the coastal communities in the Pacific may well be to rebuild the stocks by releasing cultured juveniles, and to combine this intervention with other forms of management that will protect the released animals until they, and their progeny, replenish the population to a level at which it can be managed sustainably. At that point, stock enhancement can also be evaluated as a means of maximizing the productivity in locations where there is recruitment limitation.

To date, most research on restocking of tropical sea cucumbers has focused on the sandfish, *Holothuria scabra*. This is because of the fortuitous coincidence that it is relatively easy to rear in captivity, and it is the most valuable species worldwide (Conand and Byrne, 1993). The sandfish also has several other attributes that make it particularly suitable for stock enhancement (Battaglene and Bell, 1999). In particular, it is sedentary, it inhabits inshore areas such as seagrass beds, mangroves, inner-reef flats and estuaries (Hamel *et al.*, 2001), and it can occur at very high densities, e.g. 13 500, 6 000 and 2 562 per ha, for Papua New Guinea, New Caledonia, and the Torres Strait, respectively (Shelley, 1985; FAO, 1990; Lokani *et al.*, 1996). These attributes increase the probability of monitoring restoration programmes successfully, simplify access and ownership issues, and provide for high levels of production. In addition, sandfish feed low in the food chain – they burrow in mud and sand and process organic matter, bacteria, diatoms, cyanophyceans and foraminiferans (Wiedemeyer, 1992; Mercier, Battaglene and Hamel, 1999). This means that the release of cultured sandfish is unlikely to have an impact on other fisheries species. By contrast, sandfish are believed to play a beneficial role through the bioturbation of sediments (Hammond, 1982; Massin, 1982; Wiedemeyer, 1992; Mercier, Battaglene and Hamel, 1999).

METHOD OF RESTOCKING SANDFISH

The method being developed for the restocking of sandfish involves the propagation of juveniles in hatcheries for release in the wild. Other methods for restocking sea cucumbers have been proposed, including collection, rearing and transplantation of postlarvae; induced fission; and translocation of adults. However, these methods are not suitable for the large-scale restocking of sandfish. Collection of wild juveniles is not practical because they are difficult to find, although even though the settlement habitat of postlarvae has now been identified (Mercier, Battaglene and Hamel, 2000; Hamel *et al.*, 2001). In addition, their abundance is likely to be limited as a result of overfishing, and methods for collecting them at settlement would still involve the use of aquaculture facilities for grow-out. Induced fission is not considered to be an option as it only works for a few generally lower-value species of sea cucumbers and is a slow and labour-intensive way to increase numbers (but see Reichenbach, Nishar and Saeed, 1996). Finally, the translocation of adults would only be effective where their propagules are retained, and at best would benefit some localities at the expense of others. The methods that have been developed for the propagation of juvenile sandfish are described in detail by James *et al.* (1994), Battaglene (1999), Battaglene, Seymour and Ramofafia (1999) and Pitt (2001). A summary of these methods is set out below, together with a description of the research that remains to be done to scale-up the production of juveniles needed for restocking programmes.

Collection and induction of broodstock

Like many other species of tropical sea cucumbers, sandfish can be difficult to hold in captivity. Reduced feeding, weight loss and poor gonad development are often reported for animals kept in tanks. Consequently, it is common practice to use individuals caught from the wild for broodstock. However, transport of the animals to the hatchery can pose problems. In particular, rapid changes in water temperature, salinity and pressure should be avoided because these stresses can cause evisceration and premature spawning of ripe individuals. Packing 20 individuals in separate plastic bags within a single insulated box has proved to be an effective method of transporting sandfish for periods of up to 10 h by small plane (Battaglene *et al.*, 2002).

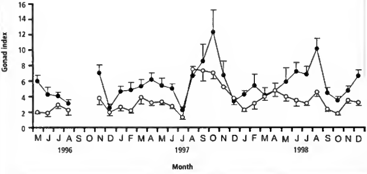
Thermal stimulation is the most commonly used method for inducing sandfish to spawn: temperatures are typically raised by 3–5 °C for 1 h. Spawning success depends on seasonal maturity and lunar periodicity. The natural reproductive cycle of sandfish has been studied in Australia, New Caledonia, Papua New Guinea and the Solomon Islands (Harriot, 1980; Conand, 1993; Ramofafia, unpublished data).

In general, this species has a biannual peak in gonadosomatic index, indicating that there are two main spawning periods each year. However, closer to the equator, e.g. in the Solomon Islands, a proportion of the population appears to spawn all year round (Figure 3). Indeed, in the Solomon Islands, it was possible to induce the production of ripe eggs each month, although the proportion of individuals that shed gametes varied from 10 percent to 50 percent. Overall, it was easiest to spawn sandfish in September, and males were easier to spawn than females.

The addition of a commercially available powdered algal product, *Schizochytrium* sp., Algamac-2000 (Bio-Marine, Hawthorne, CA, the United States) has also been used to induce sandfish to spawn: 100 g of blended Algamac is added to 1000 litres of static seawater for 1 h. However, live phytoplankton is not an effective spawning stimulant, despite the fact that phytoplankton blooms stimulate spawning in some temperate species (Hamel and Mercier, 1996a). A combination of thermal stimulation and addition of Algamac dried algae is recommended for induction of spawning in *Holothuria scabra*.

Despite the past difficulties in maintaining sandfish in tanks, it is now possible to condition this species in captivity. Battaglene *et al.* (2002) held sandfish in 4000-litre fiberglass tanks for over six months in the Solomon Islands. Spontaneous spawning occurred in >60% of animals held in tanks to which shrimp pellets were added to

FIGURE 3. Variation in gonadosomatic index of sandfish, *Holothuria scabra*, from Solomon Islands (after Ramofafia and Battaglene, unpublished data)



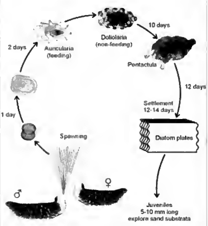
promote bacterial food production. Spawning peaked in October and continued until January when the experiment was terminated. There was also some evidence to suggest that spawning may be influenced by lunar periodicity. Ultimately, it may be possible to achieve out-of-season spawning by holding broodstock in tanks in which the temperature and photoperiod is controlled (as is practised for a number of marine fish and molluscs).

The onset of spawning in sandfish is usually preceded by rolling and agitated movements. Males typically lift half their bodies off the substrate during spawning, releasing sperm continuously for up to 3 h, whereas females spawn in a series of short powerful bursts. Females produce an average of 1.9 million eggs, but this can vary greatly among individuals. The eggs should be fertilized at a sperm density of 10 000–100 000 per ml as higher concentrations of sperm increase the incidence of deformities in holothurian larvae (YSFRI, 1991; Ito, 1995; Hamel and Mercier, 1996b). The fertilized eggs are incubated for 24 h in 250-litre tanks with conical bottoms at 28 ± 2 °C.

Larval rearing and grow-out of juveniles for restocking

As a result of several years of research by the WorldFish Center in the Pacific, and more recently in Viet Nam, methods for the larval rearing of sandfish, and grow-out of juveniles, are now fairly routine. The larval cycle is relatively short, at 14 days, and involves three separate larval stages: auricularia, doliolaria and pentaculae (Figure 4). The auricularia is the larval feeding stage and, provided adequate food is supplied, the larvae become non-feeding doliolaria during a short transition stage before settling as pentactulae (Battaglene, 1999; Pitt, 2001). Feeding of larvae with micro-algae commences on the second day after hatch at 20 000 cells/ml and gradually increases to 40 000 cells/ml after 14 days. Larvae survive and grow best on a combined diet of *Rhodomonas salina* (a red alga with a large cell size, 8–12 µm) and *Chaetoceros muelleri* (diatom, 5– to 8 µm excluding spines). However, if facilities for growing algae are limited, then the best all round choice appears to be *Chaetoceros muelleri* as it is tolerant of high temperatures and is relatively easy to grow.

FIGURE 4. The larval cycle of cultured sandfish (*Holothuria scabra*)

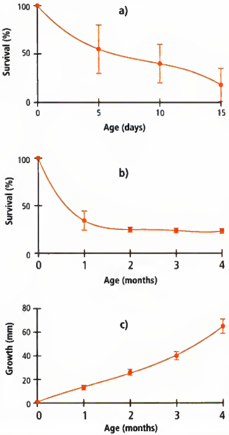


In general, there is a negative relationship between stocking density of larvae and survival to settlement. The optimal stocking density in static tanks, with water temperatures ranging from 26 to 29° C, is around 0.5 larvae/ml. Survival to settlement has been variable, ranging from <1 percent to 35 percent. Mortality is greatest at first feeding, and at settlement (Figure 5a and 5b). Preliminary experiments suggest light intensity should be kept at around 400 lux on the water surface. There is considerable scope for improving the survival of larvae and, as techniques are refined, survival to settlement will hopefully reach the 80–90 percent currently achieved with Stichopus japonicus in Japan (Ito and Kitamura, 1997; Yanagisawa, 1998).

The pentactulae larval stage of sandfish are settled on fibreglass plates that have been "conditioned" in seawater for 4–10 days outdoors under direct sunlight. Conditioning provides a bacterial film and fine coating of epiphytes and diatoms that stimulates metamorphosis and settlement of sandfish. Algamac is also added from day 10 at 1.0 g/1 000 litres as a potential settlement cue and source of food for newly settled pentactulae. Newly settled juveniles attach firmly to settlement surfaces and then have to be detached so that they can be moved from indoor larval rearing tanks to outdoor nursery tanks. This is done using a 0.5–1 percent (wt/ wt)solution of potassium chloride (Battaglene and Seymour, 1998).

There is a critical period of high mortality for newly settled juveniles within the first month of culture (Figure 5b). To combat this mortality, it is better to rear juveniles on plates rather than on hard substrata during the initial stages of outdoor culture. Once the juveniles reach a size of 20 mm, which takes an average of six weeks after settlement (Figure 5c), survival stabilizes and they can be transferred to tanks with a substratum of sand. Diatoms and epiphytic algae are the most important sources of food for cultured juveniles up to 50 mm in length and addition of powdered algae does not improve growth or survival except at high densities. Growth rates for juveniles average 0.5 mm/day (±0.03 SE) and 0.2 g/day (±0.02 SE) for the first two months after settlement. Sandfish juveniles reared in production tanks of 3 000 litres are an average of size of 65 mm (Figure 5c) and 18 g three months after settlement, i.e. a total age of four months. Growth is density dependent, however, and slows when densities reach ~ 225 g/m^2. This is equivalent to 15 individuals of 15 g/m^2.

FIGURE 5. Survival of cultured sandfish (*Holothuria scabra*) during the 15 days following hatching (a), and following settlement (b). Growth of sandfish juveniles during the first four months following settlement is also shown (c)



In summary, larval sandfish can be produced using standard marine hatchery technology, and the juveniles can be grown-out to sizes that appear to be suitable for release in the wild in 3–4 months with little or no addition of food to tanks. The development of these methods holds great promise for restocking programmes. The challenges now are to scale-up the production of juveniles to provide the tens to hundreds of thousands of individuals needed for rebuilding stocks, and to develop ways of releasing these juveniles into the wild with high rates of survival.

Scaling-up the production of juveniles

This is perhaps the most challenging part of the work remaining to be done. Unlike most fish and molluscs used in aquaculture, sandfish cannot be reared in the water column; rather, they must be associated with the substratum. At stocking densities that do not inhibit growth, a large surface area of tanks or ponds (not including hatchery facilities and settlement systems) is required to culture the great numbers of juveniles needed for effective restocking programmes. For example, a restocking programme designed to release 2 million juveniles would require more than 13 ha of grow-out ponds. Unless a cheaper way of mass-producing the juveniles can be found, there is a considerable risk that the expense involved will be a deterrent to development agencies interested in assisting SIDS with restocking sandfish.

One possible way of defraying these costs would be to combine the culture of sandfish with shrimp, thereby saving the costs of constructing and managing rearing ponds. This may be a possibility for farms dedicated to rearing *Penaeus monodon* because juvenile sandfish juveniles are one of the few species of sea cucumbers that can tolerate a reduction in salinities as low as 20 ppt (Mercier, Battaglene and Hamel, 1999). Otherwise, farms raising shrimp in normal seawater (35 ppt), e.g. those in New Caledonia for *Litopenaeus stylirostris*, may be suitable. In addition to producing a second crop for purchase by development agencies, such co-culture may also have other advantages for the shrimp farmers. These potential benefits stem from the burrowing and feeding behaviour of sandfish. Burrowing by sandfish may help to mobilize nutrients from the sediment into the water column, improving the normally low productivity of ponds early in the shrimp production cycle. The feeding and burrowing behaviour of sandfish may also help assimilate excess nutrients and bacteria towards the end of the production cycle, when eutrophication of pond water is a common problem.

Assessment of the potential for combined culture of sandfish and shrimp cannot proceed, however, until experiments are completed to determine whether there are any deleterious interactions between shrimp and sandfish. This is a possibility because *H. scabra* has sapponins in the body wall (Sotheeswaran, personal communication) that are toxic to some fish. It will also be important to perform experiments in tanks and ponds to determine whether the shrimp prey on the sandfish. The WorldFish Center and partners have undertaken some investigations of interactions between sandfish and *Penaeus monodon* in the Socialist Republic of Viet Nam, and are preparing to perform similar research involving *L. stylirostris* in New Caledonia. If deleterious interactions do not occur, methods for the development of combined culture of sandfish and shrimp in ponds will be investigated. In the event that there are damaging interactions between sandfish and shrimp, there may still be considerable scope for reducing the cost of growing-out sandfish by rearing them in the flooded drains between shrimp ponds.

An alternative to ponds, with or without shrimps, for rearing cultured juveniles for restocking programmes would be the farming methods already developed in

India and Indonesia (FAO, 1988; Daud *et al.*, 1993; Muliani, 1993; James, 1994, 1996). There, sandfish are grown-out in rectangular meshed cages anchored to the mud by wooden poles. According to James *et al.* (1994), cages need to be cleaned regularly and replenished with new substrate in order to obtain good survival and growth. Farmed juveniles are also fed various waste products, including chicken manure and the bottom sludge from prawn farming ponds. However, such methods would make it difficult to mass-produce the very large numbers of individuals needed for restocking programmes. They would also be vulnerable to vandalism, poaching and damage by storms.

RELEASE STRATEGY

In tandem with the development of methods for the cost-effective mass-production of sandfish 3–6 months of age, it is critical to determine how to release the juveniles in a way that ensures they survive to maturity in high proportions. As a prelude to the development of optimal release strategies, there has been a concerted effort to learn about the ecology of juvenile sandfish (reviewed by Hamel *et al.*, 2001).

It is now evident that recently settled juveniles occur on seagrass leaves in the wild, and that the pentactulae settle preferentially on seagrass leaves, possibly using chemical detection (Mercier, Battaglene and Hamel, 2000). Newly-settled juveniles remain on the seagrass leaves for about a month, then migrate to sand at around 6 mm in length (Mercier, Battaglene and Hamel, 2000), where they are initially cryptic. However, once they reach 10–40 mm in length, they start to display diel burrowing behaviour, emerging close to sunset and burrowing around sunrise (Mercier, Battaglene and Hamel, 1999). The recent research has also shown that juveniles of all sizes demonstrate a strong selectivity for organically rich sediments with a mean grain size of 0.4 mm, and are tolerant of salinities as low as 20 ppt (Mercier, Battaglene and Hamel, 1999). In general, juvenile sandfish can inhabit a range of shallow sandy inshore areas, suggesting that it may be possible to release them effectively in a number of habitats.

Based on what we now know about the ecology of sandfish, the lessons from restocking a temperate species of sea cucumber in Japan (Yanagisawa, 1996, 1998), and the stock enhancement of other species (Blankenship and Leber, 1995), the following factors have potential to affect the survival of released sandfish: method of transport to the release site, size at release, type of substrate, timing of releases (both within the diurnal cycle and seasonal), stocking density, abundance of predators and availability of food.

To date, there have only been short-term field experimentss to examine one of these factors: release habitat. Dance, Lane and Bell (2003) released juvenile cultured sandfish, with a mean size of 35 mm, on soft substrata near mangrove–seagrass and lagoonal coral reef flat habitats in the Western Province of the Solomon Islands. Mean survival at the mangrove–seagrass sites was 95–100 percent 1 h after release and approximated 70 percent three days later. At the coral reef flat sites, however, mean survival was as low as 37.5 percent 1 h after release and total loss occurred in two of the three releases within 48 h. The mortality was a result of predation by fish (Balistidae, Labridae, Lethrinidae and Nemipteridae). Dance, Lane and Bell (2003) also demonstrated that survival of juvenile sandfish was improved significantly by releasing them within a cage of 8-mm mesh, but did not continue the experiments for long enough to determine whether high rates of predation occurred for larger individuals in the coral habitat once the cages were removed. They concluded that, for the two habitats they studied, only the mangrove–seagrass areas should be considered for release of juvenile sandfish. They also suggested that release at night, to coincide with the time sandfish emerge during their diel burrowing cycle, and short-term use of protective cages, should be investigated to improve survival in that habitat.

The WorldFish Center is now assessing the effects of the factors listed above on the survival of juvenile cultured sandfish released into the wild. The research is being carried out in the zones of the lagoon in New Caledonia where sandfish are distributed commonly (Conand, 1989) in collaboration with the Secretariat of the Pacific Community (SPC), the Provinces and Government of New Caledonia and the French Research Institute for Exploitation of the Sea (IFREMER).

GENETIC RESOURCE MANAGEMENT

The programme to develop methods for restocking sandfish in the Pacific is paying special attention to the need to describe the genetic structure of stocks in the region, and the need to produce and release juveniles in a way that maintains the genetic diversity of these stocks. The work on stock structure has been the initiative of the Australian Institute of Marine Science (AIMS) with support from the WorldFish Center. To date, the analysis has been limited to quantifying the genetic affinities of sandfish at several inshore locations along the tropical coast of eastern Australia, and from two locations in the Solomon Islands. However, plans are in place to broaden the scope of the study to include Papua New Guinea, New Caledonia and several sites in Southeast Asia.

Although the extent of the sampling for the analysis of stock structure has been limited, some important results have already emerged. In particular, gene flow between populations from different locations on the east coast of Australia is significantly restricted (Uthicke and Benzie, 1999). Moreover, one of the two populations in the Solomon Islands is more closely related to a population in Australia than it is to the other one in the Solomon Islands, even though the two populations in the Solomon Islands are only about 20 km apart (S. Uthicke, personal communication). Other important findings from the study are that there were no significant differences between individuals from shallow and deep water, or between black and brown colour morphs, at the same general location in Australia (Uthicke and Benzie, 1999).

On the basis of the distinct structuring of sandfish stocks in the Pacific revealed by the above-mentioned study, juveniles used in field experiments to develop optimal release strategies will only be released in the same general area where the broodstock were collected. Other measures advocated to conserve the genetic diversity of sandfish stocks during field experiments and pilot-scale restocking projects will include:

(1) use of a minimum of 30 broodstock for each spawning;

(2) regular replacement of all broodstock and;

(3) release of multiple cohorts at the same site.

One problem that has emerged with these measures is that even when large numbers of broodstock are used, the effective spawning size for sandfish is low: as few as 10 percent of induced animals shed gametes. However, taken together over time, the measures listed above should greatly reduce the risk of altering the gene pool as the production and release of numerous cohorts, each with different gene frequencies, will build a released stock with gene frequencies approximating the wild population (Munro and Bell, 1997 and references therein). In other cases where this approach has been used, the resulting gene frequency of all cultured individuals combined is a close approximation to that of the wild stock (e.g. Bartley and Kent, 1990).

HEALTH MANAGEMENT

Few problems have arisen with diseases during the propagation and grow-out of sandfish but there is always a risk of transferring pathogens to the wild through the release of cultured juveniles. The only significant incidence of disease during the production of seven cohorts of sandfish in Solomon Islands between 1997 and 1999 was the loss of one tank of three-month-old sandfish to skin peeling disease. The cause of this disease is thought to be ciliated protozoans brought on by overcrowding (Yanagisawa 1998). There is no known treatment for skin peeling disease but it does not appear to be highly contagious and can be avoided through good husbandry practices.

We recommend the following quarantine procedures prior to release of juveniles:

1. removal of damaged or sick animals during the culture period;
2. placement of sandfish in tanks with hard surfaces, flow-though seawater and aeration for 48 h prior to release to evacuate intestines of sand. There should also be regular removal of sand and faecal material from the tanks during this period;
3. examination of a subsample of sandfish for external parasites and diseases prior to release;
4. removal of any algae or invertebrates associated with sandfish harvested from quarantine tanks to avoid translocation of other organisms to the wild.

The main "health" management problems facing the production of sandfish are likely to be the control of predators and competitors of the larvae, rather than the treatment of diseases per se. For example, copepods multiply in tanks receiving unfiltered water and cause mortality of the larvae by depleting food resources. The copepods can be removed with regular applications of Trichlorophos at 0.5–1 ppm for 8 h or Dipterx at 2 ppm for 2 h (James *et al.*, 1994; Ito, 1995; Yanagisawa, 1996; Ito and Kitamura, 1997). Alternatively, copepod infestations can be prevented by routine filtering of seawater with 5 μm nominal filters, and regular transfer of juveniles to clean tanks.

MONITORING AND EVALUATION

Although no large-scale releases of sandfish in the Pacific to rebuild wild stocks have yet occurred, some thought has already gone into two of the components that will be required for effective monitoring and evaluation of restocking. These components are the development of methods for measuring the success of releasing cultured juveniles, and estimates of the potential economic gains from a national restocking project.

Measures of success

There are two options for measuring the success of programmes for restocking sandfish. One involves the use of a genetic marker to identify the proportion of the rebuilt stock derived from released cultured animals; the other is based on large-scale sampling to compare abundances of sandfish at sites with and without releases.

Genetic markers provide a possible tool for measuring the success of restocking programmes because they allow the progeny of released cultured animals to be identified across generations. Genetic tags can be created by breeding programmes that confer distinctive, inherited morphology or by screening and selecting broodstock with rare alleles (Munro and Bell, 1997 and reference therein). In the case of sandfish, one such potential genetic marker can be identified easily: a significant proportion (from 10 to 60 percent) of cultured individuals are black, even when the broodstock is composed completely of "brown" morphs. However, there are some reasons why it may not be practical to use the black morph as a genetic marker. These reasons are: 1) Black adults are not common in the wild, perhaps because they are more conspicuous and harvested in greater proportions than the brown morph, which means that it may be difficult to collect sufficient black individuals for responsible broodstock management; 2) the pattern of inheritance for the black morph is unknown and thus, even if only black individuals are used in restocking programmes, there is no guarantee that their progeny will be black, or that black individuals will be produced in high proportions when black morphs interbreed with wild brown stock; 3) brown cultured juveniles would not be suitable for experimental restocking programmes. The last of these problems is only a short-term concern as, once the effectiveness of restocking has been demonstrated, there will be no necessity to mark individuals and both colour morphs can be used for releases. The other concerns would also be eliminated if sufficient numbers of wild black adults could be accumulated for responsible broodstock management, and the black morph had a very high rate of inheritance. However, the probability of overcoming these problems cannot be determined without several years of effort and research.

The other means of creating a genetic marker, by selecting broodstock with rare alleles, is more suited to situations in which the breeding animals can be kept in captivity and managed so that the rare alleles can be included in each cohort used for restocking. In the case of sandfish, where there is reliance on the use of wild broodstock, the identification of rare alleles in each batch of animals collected for spawning, and their subsequent detection to ascertain the contribution of released animals to the restored stock, would be too complicated and expensive. Further problems with this method are that the rare alleles may be deleterious to the fitness of released sandfish and, if so, this lack of fitness would be passed on to the remnant wild stock through introgression of genes during inbreeding between cultured animals (or their progeny) and wild individuals.

The time and cost required to identify effective and safe genetic tags for released sandfish, compared with the relative ease of counting sedentary sandfish in shallow water, promotes the use of sampling methods to measure the success of restocking programmes. The technique we advocate is based on the work of Underwood (1992, 1995) and depends on sampling the abundance of sandfish in the populations(s) to be restocked, and those at several unstocked (control) sites, on several occasions before and after the release of juveniles. In this case, the "after" sampling would be done once the population had been given sufficient time to recover to fishable levels (i.e. the time needed for several generations). Significantly greater abundances at restocked sites than at control sites at such times can then be attributed unequivocally to restocking, rather than to the effects of other processes influencing recruitment.

Economic analysis

The initiatives to restock sandfish in the Pacific have been based on the fact that the price for first-grade bêche-de-mer is inelastic, and the general assessment that the costs of restoration should not exceed the value of the additional production in the long term. The exact information needed to calculate whether the gains from restocking will exceed the costs will not be available until the research has been completed. This information includes: the cost of producing and releasing cultured juveniles and protecting them from fishing until robust populations are established; the survival, reproductive success and longevity of the released sandfish; the level of sustainable harvests possible each year after stocks are replenished; and the area and carrying capacity of habitat suitable for sandfish. For evaluation of subsequent stock enhancement programmes to overcome recruitment limitation, the additional information needed is simply the difference between the cost of producing and releasing juveniles and the value of the additional production.

The bêche-de-mer fishery in the Solomon Islands provides an indication of the benefits and costs of using restocking or stock enhancement to manage the resource. Throughout much of the 1980s, harvests of bêche-de-mer from the Solomon Islands were steady at about 150 tonnes per annum (Figure 1b) but, according to one of the principal exporters, the catches included only a small component of sandfish because of previous overfishing of this valuable species. Consequently, there is much potential to increase the yield of sandfish from the numerous large lagoons surrounding the high islands that comprise the nation. However, even if the increase in production was limited to 50 tonnes of bêche-de-mer, the value of the additional catch would be up to US$2.5 million because first-grade sandfish currently fetches a retail price of US$50/ kg. Approximately 25 percent of this additional revenue (i.e. US$625 000) would be expected to end up in the hands of artisanal fishers. The costs of releasing and protecting the number of juveniles needed to restore the spawning biomass of sandfish to the level at which regular additional annual harvests of 50 tonnes were possible is unknown, but may not be much more than the release of a few large, genetically diverse cohorts in close succession, provided there is widespread compliance with the necessary prohibition on fishing during the restoration period.

The option of producing and releasing enough juveniles every year to increase catches by 50 tonnes in a stock enhancement programme would be more expensive, but is still estimated to be viable. For example, we estimate that the cost of producing juvenile sandfish is around US$0.25 each in some countries, and that the release of 2 million juveniles would result in the harvest of an additional 50 tonnes. This is based on the fact that there are 10 sandfish/kg of first grade bêche-de-mer, and that the average rate of survival in other restocking programmes worldwide is 25 percent (Munro and Bell, 1997). Thus, the annual cost of producing the juveniles required to increase yields by 50 tonnes is estimated to be US$500 000. If correct, this would result in a net added value to the fishers for each release of US$625 000, equivalent to a 25 percent return on investment.

The estimate of US$0.25 per animal is conservative and based on our experience in producing juvenile sandfish of 20 mm in length. However, the price should decline significantly with further research and economies of scale. In Japan, it costs about US$0.04 to produce a juvenile *Stichopus japonicus* (Yanagisawa, 1998). This is an appropriate comparison because, in 1996, the Sea Farming Centres in Japan released a total of 2 557 000 *S. japonicus*, with an average size of 9 mm (range 1–120 mm).

As mentioned previously, the artisanal fishers in the Pacific are not in a position to organize or pay for hatcheries to restock sandfish. This will have to be done on their behalf by development agencies. It is vital, however, that such support is maintained until stocks are rebuilt and managed to produce sustainable yields because the national governments do not have the resources to complete such programmes if support is withdrawn prematurely (Bell, 1999b).

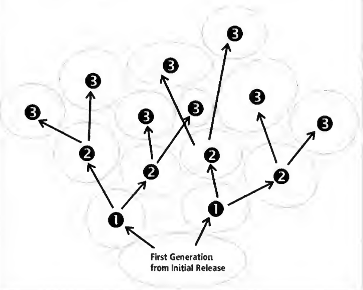
SPECIFIC MANAGEMENT REQUIRED FOR RESTOCKING

The range of management measures described earlier will need to be refined to ensure that restored sandfish stocks do not suffer recruitment and growth overfishing once the fishery is reopened. Prior to these measures, however, two specific types of management are needed for restocked populations of sandfish. The first task is to provide complete protection for the released individuals and the remnant wild stock until they and their progeny have replenished the population to the point at which substantial harvests can be sustained each year. This requires a well-policed moratorium on the capture and export of sandfish.

The second task is to manage the releases of sandfish so that the all suitable habitat is colonoized as quickly as possible. Where there is a single genetic stock and a large production facility, this can be done through multiple releases of juveniles at numerous points. However, in some Pacific Islands, there is likely to be discrete structuring of sandfish stocks and/or limited capacity to produce cultured juveniles. In such situations, the available resources may only be able to produce enough juveniles for releases at one area for each discrete stock. If so, dispersal of sandfish to all suitable habitat would be facilitated by translocation of a portion of the progeny produced at the restocked area to depleted areas within the range of the stock. Figure 6 provides an example of the gains that could be made through a well-managed translocation programme of this nature: 14 depleted areas could receive sandfish within three generations if two translocations of progeny were made from each area where spawning occurred.

The conditions that need to be met for translocations to be a responsible means of augmenting restocking programmes are: (i) the initial release has to be large and genetically diverse, (ii) sufficient juveniles need to be translocated each time to provide a genetically diverse and effective spawning biomass, (iii) the area where the progeny

FIGURE 6. Scheme for the translocation of sandfish from restocked to depleted areas to distribute juveniles to all suitable habitat. Numbers refer to the generation derived from an initial release of cultured animals. Broken lines denote area of larval dispersal of progeny of restocked sandfish



will occur can be defined, and (iv) the progeny are not transferred across stock boundaries. Owing to problems associated with achieving mass-spawning of sandfish in hatcheries, the first of these conditions may be difficult to achieve. However, it is most important that the initial release is genetically diverse because the gene frequencies will be translocated to all other areas. This may necessitate the release and spawning of several cohorts at the initial release site before translocations begin.

Whether direct hatchery releases or initial releases followed by translocations are used to rebuild the fishery, effective restocking of sandfish in the Pacific will also depend on close cooperation with fishing communities. As customary marine tenure is widespread in many Pacific countries, it will be important to ensure that all groups in control of suitable habitat for sandfish eventually receive juveniles to restock their areas. This consideration will be met by the aim to supply all suitable habitat with juveniles; however, the reality will be that some areas will receive juveniles before others. Clearly, it will aid social harmony if all communities are informed about the process, and the rationale, for the progressive distribution of juveniles. This will be particularly important where it is necessary to use translocation of progeny from one area to another.

The need to work with communities is not limited to the period required for rebuilding of the stock: communities will also be responsible for management of sandfish stocks once exports are permitted and so will need information about how best to sustain catches. There will also be the need for cooperation among communities in setting levels of catch because mismatches will occur between the distribution of a discrete stock and the area under the tenure of a community, such that effective management will depend on a unified approach by several communities. Regular communication with all communities during the rebuilding phase about the merits of the restocking programme, and the management measures that should be applied once the fishery reopens, will greatly enhance the likelihood of successful and cooperative community-based management of sandfish stocks.

SUMMARY AND CONCLUSIONS

Restocking with hatchery-reared juveniles has great potential to help Pacific Islands break the long-term "boom and bust" cycle of the bêche-de-mer fishery. The main benefit of restocking is that it provides a way to "fast-track" the restoration of stocks to the point where they can be managed for sustainable yields.

There are four steps to delivering the benefits promised by restocking: (1) development of methods for the mass-production of juveniles, (2) learning how to release the cultured sandfish in the wild so that they survive in high proportions, (3) protecting the released sea cucumbers until stocks are replenished and (4) managing the restored stocks to obtain sustainable harvests of first-grade bêche-de-mer (i.e. large individuals). The same technology used for restocking can then be applied to supplement the yields of restored stocks by releasing cultured juveniles in stock enhancement programmes to overcome recruitment limitation. This would allow the production of sandfish to approach the carrying capacity of the habitat.

Although the way to restore and manage the fishery for sea cucumbers in the Pacific is now apparent, only some of the technology and procedures needed to achieve these goals are currently in place. Furthermore, the research has been confined largely to just one species, sandfish (*Holothuria scabra*). The major challenges remaining for restocking of sandfish are: learning how to scale-up the rearing techniques to produce the hundreds of thousands of juveniles needed to have an impact on the abundance of stocks; developing effective strategies for releasing cultured juveniles in the wild; and assessing the economic viability of restocking. In all three cases, however, there is cause for optimism. If research underway to investigate the potential for co-culture of sandfish and shrimp is successful, the mass-production of juvenile sandfish may be possible as a by-crop of shrimp farming. Otherwise, it should be possible to mass-produce sandfish in dedicated ponds, albeit at greater cost. There is no obvious impediment to the development of release strategies, nor are there any apparent reasons why it cannot be done in a responsible way. For example, guidelines are in place for the management of broodstock to maintain genetic diversity, the risk of introducing diseases to conspecifics and other species appears to be low, and the fact that sandfish are low in the food chain means that there should be little or no impact on other fisheries species. Preliminary estimates also indicate that restocking should be economically viable in terms of returns to artisanal fishermen, although we hasten to point out that such an evaluation cannot be done thoroughly until the necessary research has been completed.

The key to harnessing the potential benefits of restocking sandfish is support for the programmes from regional/international research organizations, fishing communities, governments and development agencies. The regional/international research organizations need to complete the development of cost-effective methods for restocking sandfish so that this tool is ready for application throughout the Pacific. The fishing communities need to be prepared to forego catches until the stocks are rebuilt, and then to comply with the advice and/or regulations designed to ensure that yields of high value can be obtained each year.

Governments must provide the framework for this process by implementing a moratorium on the export of sandfish until the stocks recover, applying a total export quota based on sustainable yields when the fishery is reopened and ensuring that there is compliance with these laws. Finally, as most governments in the Pacific do not have the financial or human resources to produce the very large numbers of juveniles required to replenish stocks, support is needed from development agencies for restocking programmes. They could also assist by contributing to the costs of developing the measures needed for sustainable management of the restored fishery.

Overall, the prospects for restocking sandfish look particularly promising and every effort should be made to bring this potential management tool to the attention of fishing communities, governments and development agencies so that they stand ready to support and implement restocking programmes as soon as the full suite of methods required becomes available.

ACKNOWLEDGEMENTS

The research described in this paper was supported substantially by grants from the Australian Centre for International Agricultural Research (ACIAR) and the Canadian Institute for Development Assistance (CIDA). We thank Peter Gardiner for comments on the manuscript.

References

Adams, T. 1992. Resource aspects of the Fiji bêche-de-mer industry. South Pacific Commission Bêche-de-mer. *Information Bull.*, 4: 13–16.

Adams, T. 1998. Coastal fisheries and marine development issues for small islands. In M.J. M. J. Williams, ed. *A roadmap for the future for fisheries and conservation.* ICLARM Conference Proceedings No. 56: 40–50.

Aswani, S. 1997. Troubled water in South-western New Georgia Solomon Islands: is codification of the commons a viable avenue for resource use regulation? *South Pacific Commission Traditional Marine Resource Management and Knowledge Information Bulletin*, 8: 2–16.

Bartley, D.M. & Kent, D.B. 1990. Genetic structure of white seabass populations from the southern California Bight region: applications to hatchery enhancement. *Calif. Coop. Fish Invest. Rep.*, 31: 97–105.

Battaglene, S.C. 1999. Culture of tropical sea cucumbers for the purposes of stock restoration and enhancement. *NAGA, The ICLARM Quarterly*, 22(4): 4–11.

Battaglene, S.C. & Bell, J.D. 1999. Potential of the tropical Indo-Pacific sea cucumber, *Holothuria scabra*, for stock enhancement. In B. R. Howell, E. Moksness & T. Svåsand, eds. *Stock enhancement and sea ranching*, pp. 478–490. Oxford, UK, Fishing News Books, Blackwell Science.

Battaglene, S.C. & Seymour, E.J. 1998. Detachment and grading of the tropical sea cucumber sandfish, *Holothuria scabra*, juveniles from settlement substrates. *Aquaculture*, 159: 263–274.

Battaglene, S.C., Seymour, E.J. & Ramofafia, C. 1999. Survival and growth of cultured juvenile sea cucumbers *Holothuria scabra*. *Aquaculture*, 178: 293–322.

Battaglene, S.C., Seymour, J.E., Ramofafia C. & Lane, I. 2002. Spawning induction of three tropical sea cucumbers, *Holothuria scabra*, *Holothuria fuscogilva and Actinopyga mauritiana*. *Aquaculture*, 207: 29-47.

Bell, J.D. 1999a. Aquaculture: a development opportunity for Pacific Islands. Development Bull., 49: 49–52.

Bell, J.D. 1999b. Transfer of technology on marine ranching to small island states. In (unedited) Marine ranching: global perspectives with emphasis on the Japanese experience. *FAO Fisheries Circular no.*, 943: 53–65.

Bell, J.D. 1999c. Restocking giant clams: progress, problems and potential. In B. R. Howell, E. Moksness & T. Svåsand, eds. *Stock enhancement and sea ranching*, pp. 437–452. Oxford, UK, Fishing News Books, Blackwell Science.

Bennett, J.A. 1987. *Wealth of the Solomons.* Pacific Islands Monograph Series, No. 3, University of Hawaii, USA. 529 pp.

Blankenship, H.L. & Leber, K.M. 1995. A responsible approach to marine stock enhancement. *American Fisheries Society Symposium*, 15: 167–175.

Conand, C. 1989. Les holothuries aspidochirotes du lagon de Nouvelle-Caledonie: biologie, ecologie et exploitation. Paris 393 pp. (Etudes et Theses ORSTOM)

Conand, C. 1993. Reproductive biology of the holothurians from the major communities of the New Caledonia Lagoon. *Mar. Biol.*, 116: 439–450.

Conand, C. 1997. Are holothurian fisheries for export sustainable? *Proceedings of the Eighth International Coral Reef Symposium*, pp. 2021–2026.Vol. 2, Panama.

Conand, C. & Byrne, M. 1993. A review of recent developments in the world sea cucumber fisheries. *Mar. Fish. Rev.*, 55(4): 1–13.

Conand, C. & Sloan, N.A. 1989. World fisheries for echinoderms. *In* J. F. Caddy, ed. *Marine invertebrate fisheries: their assessment and management*, pp. 647–663. Chichester, UK, Wiley.

Dalzell, P. 1990. Bêche-de-mer production from three Papaun New Guinean atolls between 1982 and 1983. *South Pacific Commission Bêche-de-mer Information Bull.*, 1: 6–7.

Dalzell, P., Adams, T.J.H. & Polunin, N.V.C. 1996. Coastal fisheries in the Pacific Islands. *Oceanogr. Mar. Biol.: an Annual Review*, 34: 395–531.

Dance, S., Lane, I. & Bell, J.D. 2003. Variation in short-term survival of cultured sandfish (*Holothuria scabra*) released in mangrove-seagrass and coral reef flat habitats in Solomon Islands. *Aquaculture*, 220: 495-505.

Daud, R., Tangko, A.M., Mansyur, A. & Sudradjat, A. 1993. *Polyculture of sea cucumber, Holothuria scabra and seaweed, Eucheuma sp in Sopura Bay, Kolaka Regency Southeast Sulawesi. In* A. Sudradjat, ed. Prosiding Seminar Hasil Penelitian Perikanan Budidaya Pantai, 16–19 July 1993, Maros, pp. 95–98.

Doherty, P.J. 1999. Recruitment limitation is the theoretical basis for stock enhancement in marine populations. In B. R. Howell, E. Moksness & T. Svåsand, eds. Stock enhancement and sea ranching, pp. 9–21. Oxford, UK, Fishing News Books, Blackwell Science.

Eldredge L.G. 1994. *Perspectives in aquatic exotic species management in the Pacific Islands. Vol. I. Introductions of commercially significant aquatic organisms to the Pacific Islands.* New Caledonia, South Pacific Commission.

FAO. 1988. *Sea cucumber culture: potential and prospects*, by B. Tiensongrusmee & S. Pontjoprawiro. Seafarming Development Project, United Nations Development Programme, Executing Agency, Food and Agriculture Organization of the United Nations. (INS/81/008/Manual 14). Rome.

FAO. 1990. *The fishery resources of Pacific Island countries.* Part 2. *Holothurians*, by C. Conand. FAO Fisheries Technical Paper, 272.2. Rome.

Hamel, J.-F. & Mercier, A. 1996a. Early development, settlement, growth, and spatial distribution of the sea cucumber *Cucumaria frondosa* (Echinidermata: Holothuroidea). *Can. J. Fisheries Aquatic Sci.*, 53: 253–271.

Hamel, J.-F. & Mercier, A. 1996b. Gamete dispersion and fertilisation success of the sea cucumber *Cucumaria frondosa. South Pacific Commission Bêche-de-mer Information Bull.*, 8: 34–40.

Hamel J.-F., Conand, C., Pawson, D. & Mercier, A. 2001. The sea cucumber *Holothuria scabra* (Holothuroidea: Echinodermata): its biology and its exploitation as bêche-de-mer. *Adv. Mar. Biol.*, 41:129-223.

Hammond, L.S. 1982. Analysis of grain-size selection by deposit-feeding holothurians and echinoids (Echinodermata) from a shallow reef lagoon, Discovery Bay, Jamaica. *Mar. Ecol. Progr. Ser.*, 8: 25–36.

Harriot, V.J. 1980. *Ecology of the holothurian fauna of Heron Reef and Moreton Bay.* University of Queensland, Brisbane, Australia. 153 pp. (M.Sc. thesis).

Holland, A. 1994a. *The status of global bêche-de-mer fisheries with special reference to Solomon Islands and the potentials of holothurian culture.* University of Newcastle, UK. 133 pp. (M.Sc. thesis)

Holland, A. 1994b. The bêche-de-mer industry in the Solomon Islands: recent trends and suggestions for management. *South Pacific Commission Bêche-de-mer Information Bull.*, 6: 2–9.

Ito, S. 1995. *Studies on the technical development of the mass production for sea cucumber juvenile, Stichopus japonicus.* Saga Prefectural Sea Farming Center, Japan. 87 pp.

Ito, S. & Kitamura, H. 1997. Induction of larval metamorphosis in the sea cucumber *Stichopus japonicus* by periphitic diatoms. *Hydrobiologia*, 358: 281–284.

James, D.B. 1994. Seed production in sea cucumbers. *Aquaculture Int.*, 1(9): 15–26.

James, D.B. 1996. Culture of sea-cucumber. *Indian Central Marine Fisheries Research Institute Bull.*, 48: 120–126.

James, D.B., Rajapandian, M.E., Gopinathan, C.P. & Baskar, B.K. 1994. Breakthrough in induced breeding and rearing of the larvae and juveniles of *Holothuria* (Metriatyla) *scabra* Jaeger at Tuticorin. *Indian Central Marine Fisheries Research Institute Bull.*, 46: 66–70.

Lam, M. 1998. Consideration of customary marine tenure system in the establishment of marine protected areas in the South Pacific. *Ocean Coastal Manage.*, 39: 97–104.

Lawrence, J. 1999. ACIAR and ICLARM: Partners for progress in mariculture. *Partners in Research for Development*, 12: 2–10.

Lee, C.L., Dwiono, S.A.P., Amos, M., Tetelepta, M. & Rebhung, F. 1998. *Reseeding research of the topshell Trochus niloticus in northern Australia, eastern Indonesia and the Pacific.* Report to Australian Centre for International Agricultural Research (ACIAR). 337 pp.

Lincoln-Smith, M. P., Bell, J. D., Ramohia, P. and Pitt, K. A. 2000. Testing the use of marine protected areas to restore and manage tropical multispecies invertebrate fisheries at the Arnavon Islands, Solomon Islands. *Great Barrier Reef Marine Park Authority Research Publication No. 69*, 72 pp.

Lokani, P. 1995. Illegal fishing for sea-cucumber (bêche-de-mer) by Papua New Guinea artisanal fishermen in the Torres Strait protected zone. Joint FFA/SPC workshop on the management of South Pacific Inshore Fisheries, 26 June – 7 July 1995, Noumea, New Caledonia, pp. 279–288. South Pacific Commission.

Lokani, P., Polon, P. & Lari, R. 1996. Fisheries and management of bêche-de-mer fisheries in Western Province of Papua New Guinea. *South Pacific Commission Bêche-de-mer Information Bull.*, 8: 7–11.

Lucas J.S. 1994. The biology, exploitation, and mariculture of giant clams (Tridacnidae). *Rev. Fish. Sci.*, 2(3): 181–223.

Massin, C. 1982. Food and feeding mechanisms: Holothuroidea. *In* M. Jangoux & J. M. Lawrence, eds. *Echinoderm nutrition*, pp. 493–497. Rotterdam, the Netherlands, A. A. Balkema.

Mercier, A., Battaglene, S. & Hamel, J.-F. 1999. Daily burrowing cycle and feeding activity of juvenile sea cucumbers *Holothuria scabra* in response to environmental factors. *J. Exp. Mar. Biol. Ecol.*, 239: 125–156.

Mercier, A., Battaglene, S.C. & Hamel, J.-F. 2000. Settlement preferences and early migration of the tropical sea cucumber *Holothuria scabra. J. Exp. Mar. Biol. Ecol.*, 249: 89–110.

Muliani, 1993. Effect of different supplemental feeds and stocking densities on the growth rate and survival of sea cucumber, *Holothuria scabra*, in Tallo river mouth, South Sulawesi. *J. Penelitian Budidaya Pantai*, 9(4): 15–22.

Mungoa-Licuanan, S. S. & Gomez, E.D. 1996. Giant clam culture. *In* S. S. De Silva, ed. *Perspectives in Asian fisheries*, pp. 281–299. Manila, Asian Fisheries Society.

Munro, J.L. 1993a. Giant clams. *In* A. Wright & L. Hill, eds. *Nearshore marine resources of the South Pacific*, pp. 431–449. Suva, Institute of Pacific Studies; Honiara, Forum Fisheries Agency; Canada, International Centre for Ocean Development.

Munro, J.L. 1993b. Strategies for re-establishment of wild giant clam stocks. In P. E. Munro, ed. *Genetic aspects of conservation and cultivation of giant clams*, pp. 17–20. Manila, ICLARM Conference Proceedings No. 39.

Munro, J.L. & Bell, J.D. 1997. Enhancement of marine fisheries resources. *Rev. Fisheries Sci.*, 5(2): 185–222.

Nash, W.J. 1993. Trochus. In A. Wright & L. Hill, eds. *Nearshore marine resources of the South Pacific*, pp. 452–95. Suva, Institute of Pacific Studies; Honiara, Forum Fisheries Agency; Canada, International Centre for Ocean Development.

Preston, G.L. 1993. Bêche-de-mer. In A. Wright & L. Hill, eds. *Nearshore marine resources of the South Pacific*, pp. 371–407. Suva, Institute of Pacific Studies; Honiara, Forum Fisheries Agency; Canada, International Centre for Ocean Development.

Pitt, R. 2001. Review of sandfish breeding and rearing methods. *Secretariat of the Pacific Community Bêche-de-Mer Information Bull.*, 14: 14–21.

Reichenbach, N., Nishar, Y. & Saeed, A. 1996. Species and size-related trends in asexual propagation of commercially important species of tropical sea cucumbers (Holothuroidea). *J. World Aquaculture Soc.*, 27: 475–482.

Richards, A.H., Bell, L.J. & Bell, J.D. 1994. Inshore fisheries resources of Solomon Islands. *Mar. Pollution Bull.*, 29: 90–98.

Richmond, R. 1997. Reproduction and recruitment in corals: critical links in the persistence of reefs. In C. Birkeland, ed. *Life and death of coral reefs*, pp. 175–196. New York, Chapman and Hall.

Rowe, F.W.E. & Gates, J. 1995. Echinodermata. In A. Wells, ed. *Zoological catalogue of Australia*, Volume 33, pp. 294–295. Melbourne, Australia, CSIRO.

Shelley, C.C. 1985. *Potential for re-introduction of a bêche-de-mer "fishery" in the Torres Strait.* Torres Strait Fisheries Seminar, 11–14 February 1985, Port Moresby.

Shelley, C.C. 1988. *The status of the bêche-de-mer fishery in Queensland.* Workshop on Pacific Fishery Resources, 14–25 March 1988, Noumea, New Caledonia, South Pacific Commission.

Underwood, A.J. 1992. Beyond BACI: the detection of environmental impact on populations in the real, but variable, world. *J. Exp. Mar. Biol. Ecol.*, 161: 145–178.

Underwood, A.J. 1995. Detection and measurement of environmental impacts. In A. J. Underwood & M. G. Chapman, eds. *Coastal marine ecology of temperate Australia*, pp. 311–324. Sydney, Australia, University of New South Wales Press.

Uthicke, S., Benzie, J. 1999. Allozyme variation as a tool for bêche-de-mer fisheries management: a study on *Holothuria scabra* (sandfish). *Secretariat of the Pacific Community Bêche-de-mer Information Bull.*, 12: 18–23.

Wiedemeyer, W.L. 1992. *Feeding behaviour of two tropical holothrians Holothuria (Metriatyla) scabra (Jager 1833) and H. (Halodeima) atra (Jager 1833), from Okinawa, Japan*, pp. 863–870. Proceedings of the Seventh International Coral Reef Symposium. Vol. 2, Guam.

Wright, A. & Hill, L. 1993. *Nearshore marine resources of the South Pacific.* Suva, Institute of Pacific Studies; Honiara, Forum Fisheries Agency; Canada, International Centre for Ocean Development.

Yanagisawa, T. 1996. Sea-cucumber ranching in Japan and some suggestions for the South Pacific. *In* Present and future of aquaculture research and development in Pacific Island countries, pp. 387–411. Proceedings of the international workshop held at Nuku'alofa, Tonga, November 1995.

Yanagisawa, T. 1998. Aspects of the biology and culture of the sea cucumber. In S. S. De Silva, ed. *Tropical mariculture*, pp. 292–308. London, Academic Press.

Yellow Sea Fisheries Research Institute (YSFRI) 1991. *Training manual on breeding and culture of scallop and sea cucumber in China*. Scallop and Sea Cucumber Breeding and Culture Training Course, Regional Seafarming Development and Demonstration Project. (RAS/90/002).

Sturgeon stocking programme in the Caspian Sea with emphasis on Iran

Hossein Abdolhay
Director of Fish Reproduction and Stock Enhancement
No. 250 Fatemi St., Tehran, Iran

INTRODUCTION

The sturgeons of the Caspian Sea are considered highly valuable species. The Caspian Sea has traditionally been regarded as the sea of sturgeon since it produces more than 90 percent of the world's caviar. Despite a remarkable decline of sturgeon numbers over recent years, the Caspian Sea still continues to be of considerable importance in sturgeon fisheries. In 1997, the global landing of sturgeon amounted to 6 126 million tonnes, which the Caspian Sea sturgeon catch accounted for 3 872 million tonnes (FAO, 1999).

At the turn of the last century (1900) the former Soviet Union used to produce some 29 000 million tonnes of sturgeon. The fishery decreased operation following the First World War (1921–26) resulting in dramatic decreases in catch down to 1 100 million tonnes, which in turn boosted the sturgeon stocks in these years.

Numerous sturgeon hatcheries were created as mitigation for lost spawning habitat as a result of dam construction in the former Soviet Union and the Islamic Republic of Iran. With the partial destruction of natural sturgeon spawning grounds the artificial breeding of sturgeon species and fingerling release was started in the former Soviet Union in 1955 (Ivanov and Majinic, 1997). The same trend began in Iran in 1970 through the assistance of Russian fisheries technicians (Abdolhay, 1997). The growth in sturgeon fingerling released grew to such an extent that production reached 100 million fingerlings in 1985. The production and release of sturgeon fingerling continued by the establishment of 11 sturgeon hatchery centres in USSR along with three and five hatchery centres in Azerbaijan and Iran respectively; hatcheries played a crucial role in rehabilitation and restoration of sturgeon stocks. After fingerling production, release to the sea and fisheries management the capture increased to 28 000 million tonnes in 1977. During this period, sturgeon catch in Iran ranged from 1 500–2 500 million tonnes.

In the 1990s, there was a sharp decline in sturgeon stocks due to ecological changes caused by human activities (i.e. illegal fishing). The catch of sturgeon fish plummeted from 28 126 million tonnes in 1980 to 3 872 million tonnes in 1997 (FAO, 1999).

In this article, attempts are made to briefly review the sturgeon landing in recent years as well as the production and release of sturgeon fingerlings and the role hatcheries play in the development of the sturgeon fisheries in the Caspian Sea.

The Caspian Sea

In the Caspian Sea there are more than 123 species and subspecies of fish in 17 families (Kazancheev, 1981) including five species of sturgeon *Acipenser persicus* (Persian sturgeon), *Acipenser gueldenstadti* (Russian sturgeon), *Acipenser nudiventris* (ship sturgeon), *Acipenser stellatus* (sevruga), and *Huso huso* (beluga). Their roe is processed into black roe or caviar, one of the most expensive luxury food items obtained from the aquatic environment. The trade name for caviar from the Persian sturgeon, Russian sturgeon and ship sturgeon is ossetra and the two other types of caviar are named as the sturgeon they come from, i.e. sevruga and beluga.

TABLE 1. Coastline of the Caspian Sea

Country	Coastal length (km)
Azerbaijan	850
Iran	992
Kazakhstan	2200
Russia	695
Turkmenistan	1642
Total	6 379

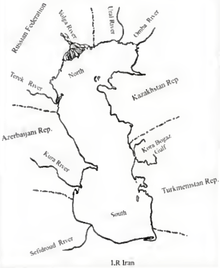
The Caspian Sea is surrounded by five countries: Azerbaijan, Iran, Kazakhstan, the Russian Federation and Turkmenistan (Figure 1). The perimeter is about 6 380 km of which 992 km is in Iran (Table 1). Total sea surface area is about 386 000 km^2, with fluctuations owing to changes in water level.

The Caspian Sea is approximately 1 200 km long and 310 km wide. It is divided into three basins. The most northerly basin is shallow, and covers an area of 80 000 km^2. The middle basin is a separate depression of some 138 000 km^2. The deepest part, 800 m, is located in the west, with a long gently rising slope to the east. The average depth is calculated to be 190 m. The southern basin, which is of particular importance to Iranian fisheries, is separated from the central part by the Absheron underwater ridge. The total area is over 168 000 km^2, which represents over 40 percent of the entire Sea. The deepest area of the depression, which lies considerably to the south of the Kura River delta off the coast of Gilan, in the west is over 1 000 m in depth. There are several ridges occurring in this area but, to the east of the depression, the sea bed is a gently rising slope and the mean depth of the basin is estimated to be 100 m (Faraji *et al.*, 1995).

The southern shoreline is relatively smooth, with several safe anchorages. There are two major inlets of importance from a fisheries point of view: to the west, the Anzali lagoon and in the east of Golestan Province, the Gorgan Gulf.

The level of the Caspian Sea, which is below sea level, fluctuates considerably as a result of climate changes in the drainage basins and, to a large degree, changes of the Volga River flow. In recent years the level of the Caspian Sea has been referenced to the level of the Baltic Sea. For the first three decades of the last century the level remained around 26 m below the level of Baltic. This was followed by a period of fluctuation during which a minimum of -28.4 m was recorded. The most recent rise of level began in 1978, reaching -26.9 m by 1994. This was attributed to increased river flow, improved surface precipitation with a subsequent reduction in evaporation, and a decrease of flow into the Kora Bogaz Gulf.

FIGURE 1. The Caspian Sea and surrounding area, with its major tributaries



The level continues to rise and low coastal areas have been inundated. Predictions are that, although the intensity may decrease, the sea level will continue to rise and may reach -26 m by 2 010 and even 1 m less some 15–20 years later. After that, a period of stability, or even decrease in levels, is predicted.

Wind-induced water surges, which may cause economic damage, are a regular feature of the Caspian Sea. Although they occur throughout the region they are particularly severe in the shallow northern reaches. Their effect in southern areas is not so serious. Sea ice appears in the northern areas in November and, during a particularly hard winter, may cover the whole area of the northern Caspian. In the middle basin, however, ice formations generally occur in December and January and are of local origin in the east, when shallow bays may be frozen over. Ice appearing in the west mostly drifts from the north. Ice is not a problem in the southern part of the Caspian. The water currents are primarily wind-generated, although in the north they are influenced strongly by river inflow. In the south, currents correlate with wind direction and are typically towards the north and north-west, or south and south-east. Localised baroclinic currents and seiches are also noted, but it is not known if these have any particular influence upon fish movements, particularly of the kilka (*Clupeonella engralliformis, C. grimmi* and *C. cultriventris*). In the north, salinity ranges from 0.1 ppt at the mouth of the River Volga and River Ural, to 10–11 ppt near the middle part of the Sea. In the south, surface salinity is around 12.6–13.5 ppt, increasing from north to south and from west to east. There is reportedly a slight increase in salinity with depth.

Water temperatures vary with latitude. In the south there is a horizontal homogeneity, with typical surface temperatures varying between 24°C and 28°C in summer. Warmer waters are to the east. In winter months these could be reduced by as much as 10°C.

The main rivers supplying the Caspian Sea are the Volga (in the Russian Federation), Kura (in Azerbaijan) and Ural (in Kazakhstan) providing 80 percent, 6 percent, and 5 percent of the inflow, respectively. Although there are many small rivers originating in Iran, they exert only a localised influence upon the hydrology of the region. Original breeding and nursery grounds for anadromous species and the environment of several rivers has been adversely affected by the construction of dams for irrigation purposes.

The Caspian Sea fisheries in Iran

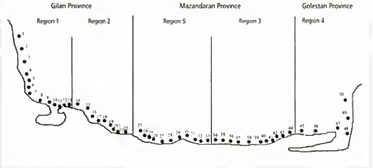
The sturgeon fishery in the Caspian Sea contributes both in food supply and providing employment in northern part of Iran. According to the Iranian fishery management plan all commercially exploitable fish in the South Caspian Sea are divided into three groups.

First group: Distant water fishery which is mainly herring (clupeidae such as *C. engralliformis, C. grimmi* and *C. cultriventris*). The herring fishery in the southern Caspian Sea started in 1939. An extensive fishery began in 1987 with total harvest of 4 170 million tonnes. The annual landing of herring increased to 82 200 million tonnes in 1998.

Second group: The coastal fishery operates mainly on six families: Cyprindae, Mugilidae, Clupeidae, Salmonidae, Percidae and Esocidae that are mainly harvested by beach sine. Average landing of these fish was 15 000 million tonnes in 1997.

Third group: Sturgeon fishery, the most valuable of the Caspian Sea, is the major economic resource and plays a significant role in the income of the Iranian south Caspian Sea fisheries.

FIGURE 2. The five SHILAT regions of the Iranian coastline, together with the 50 sturgeon stations



For administrative purposes, SHILAT (Iranian Fisheries Company) has divided the Iranian coast line of some 992 km length into five regions. From west to east, these are (Figure 2):

Gilan Province

- Region 1 - headquarters in Bandar Anzali, with 13 fishing stations.
- Region 2 - headquarters in Keyashar, with jurisdiction over nine fishing stations.

Mazandaran Province

- Region 5 - headquarters in Nowshahr, with 11 fishing stations.
- Region 3 - headquarters in Babolsar, with 11 fishing stations.

Golestan Province

- Region 4 - headquarters in Ashuradeh, with six fishing stations.

Sturgeon fishing methods in the Southern Caspian Sea

The catches of sturgeon in the sea began at the end of the last century; previously, sturgeon was caught in rivers (Barannikova, 1991). In the southern part of the Caspian Sea (Iranian side) most of the sturgeon catches are made around the rivers. As the result of legislative restrictions on gear (for protecting the sturgeon) only gillnets have been used for catching the sturgeon.

The Iranian Fisheries Company is in charge of both managing and fishing sturgeon. Three provinces, Gilan, Mazandaran and Golestan, are located in the southern part of the Caspian Sea, each with a general fisheries office and a research and training organization. Four fishing districts in these provinces were established in 1970 (districts were increased in 1987 to five) for managing and organizing sturgeon fisheries, and each district has several fishing stations from which sturgeon captured by fishermen are delivered for processing of caviar. Sturgeons are fished only by anchored gillnets, although sometimes a few may be caught by beach seine, when

TABLE 2. Standard mesh size, and length and width of gillnets used for fishing different species of sturgeon in the southern part of the Caspian Sea

Species	Mesh size (mm)	Meshes and length (m)	Width (meshes)
Acipenser stellatus	100	164 (18m)	21
Acipenser persicus	150	120 (18m)	18
Acipenser guldenstadti	150	120 (18m)	18
Huso huso	280	64 (18m)	7

fishing for teleost fishes. The standard mesh sizes (knot to knot) and length and width of gillnets used for capturing different sturgeons in the south part of the Caspian Sea are given in Table 2.

The number of nets used for capturing the sturgeon in the south Caspian depends on the fishing season and varies between the districts. Usually the number of nets used daily for each district varies between 100 to 200. The standard mesh size for Beluga until 1988 was 250 mm, but then mesh size was increased to 280 mm to prevent catches of young fish. It should be noted that, with regard to the fishery management policy fishermen have to release any immature fish caught and they are not permitted to catch ship sturgeon (*A.nudiventris*) because it is endangered. The gillnets have a length of 18 m, their lower edge rests on the sea bed during the autumn fishing season (August to October) but the nets are raised a few meters in the spring season (February to June). The sea bed is sandy over almost the whole fishing area. The sturgeon-fishing calendar for different districts is given in Table 3.

Review of fishery in the Caspian Sea

Historically the exclusive rights to fishing and other uses of the Caspian Sea belonged to the Russian Empire. In 1828, by treaty, Persian trade vessels were granted the right to navigate its waters on an equal basis with Russian ships. This was further endorsed by an exchange of letters between the two countries in 1921 and again in 1940. On both occasions it was agreed that, except for a 10-mile exclusive fishing zone, the Caspian Sea in legal terms was an area beyond the national jurisdiction of each, and where both countries had equal rights to its utilisation.

Recent history of harvest in the former Soviet Union

In the former Soviet Union, some 29 000 million tonnes per year of sturgeon were landed in 1900s but the recession in fishing operation caused by the First World War and the internal war during 1921–26 resulted in the decrease of landing down to 1 100 million tonnes which in turn improved the sturgeon stocks (Ivanov and Majinic, 1997).

In 1938 the sturgeon catch was restricted and in 1962-65 the sturgeon fishing at sea was banned in the Soviet Union, and sturgeon fishing was only allowed in the rivers. Such a ban on the fisheries could foster the migration of sturgeon species to rivers and from 1975 to 1981 the catch increased to 20 000–25 000 million tonnes (Table 4).

TABLE 3. Sturgeon fishing calendar in different fishing districts in the southern part of the Caspian Sea (Taghavi Motlagh, 1996)

Season	District	Species			
		A. stellatus	*A. persicus*	*A. guldenstadti*	*Huso huso*
Spring	1	Feb. 8 – Jun. 21	Feb. 8 – May 22	Feb. 8 – May 22	no fishing
Spring	2	Feb. 8 – Jun. 21	Feb. 8 – May 22	Feb. 8 – May 22	no fishing
Spring	3	Feb. 8 – Jun. 21	Feb. 8 – May 22	Feb. 8 – May 22	no fishing
Spring	4	Jan. 21 – May 31	Aug. 12 – May 22	Aug. 12 – May 22	Sep. 23 – Oct. 12
Spring	5	Jan. 21 – May 31	Aug. 12 – May 22	Aug. 12 – May 22	Sep. 23 – Oct. 12
Autumn	1	no fishing	Aug. 2 – Oct. 12	Aug. 2 – Oct. 12	Aug. 23 – Oct. 12
Autumn	2	no fishing	Aug. 2 – Oct. 12	Aug. 2 – Oct.12	no fishing
Autumn	3	no fishing	Aug. 2 – Oct. 12	Aug. 2 – Oct. 12	no fishing
Autumn	4	no fishing	Aug. 12 – May 22	Aug. 12 – May 22	Sep. 1 – Apr. 4
Autumn	5	no fishing	Aug. 2 – Oct. 12	Aug. 2 – Oct. 12	no fishing

The catch of sturgeons amounted to 20 000–27 000 million tonnes during 1975–86. A decreasing trend started in 1987 and continues at present (Table 4). The collapse of the Soviet Union has further aggravated the situation to such an extent that officially reported sturgeon landing plummeted to 2 900 million tonnes in 1995 (Ivanov and Majinic, 1997).

Recent history of harvest in Iran

In Iran, the sturgeon fishery is a government monopoly. Traditionally the fishery takes place in the estuaries of the coastal rivers based on an agreement signed between Iran and the former Soviet Union. Every year, fisherman paid by the Iranian government set out to sea on pre-planned schedule for catching sturgeon. The catch figures for sturgeon are given in Table 4. A stable trend in the fisheries is noticeable between 1975 to 1985, the highest catch was recorded in 1991, (3 036 million tonnes). After the collapse of the Soviet Union, there was a downward tendency in sturgeon landings that continued up to the present time. The capture fisheries in Iran were often between six percent to ten percent of that of Russia.

Fishing operations are carried out from small fibreglass vessels powered with 48 hp outboard engines. The only gear permitted is the gillnet with mesh that is especially suited for the targeted species (as discussed in **Sturgeon fishing methods in the Southern Caspian Sea** section). The complement of fishermen in each boat is four, except in Region 3 where there are only three.

Principal problems with fishery

Oil and industrial pollution is a serious danger to fisheries in the region. The source of pollution of the Northern Caspian Sea is oil production on the Mangyshlak Peninsula (Kazakhstan). When drilling for oil on the shore during the period of the sea level fluctuations and under the influence of winds, a large amount of oil is discharged into the sea. The discovery of new production fields in the sea and possible oil blow-outs may lead to the destruction of feeding grounds in the eastern part of the Northern Caspian Sea. Oil pollution in the Southern Caspian (Azerbaijan) is also a problem (Vlasenko, 1994).

Pollution problems notwithstanding the main troubles began after the dissolution of the Soviet Union in 1991. Instead of one government with centralised control of the catch, four independent countries (the Russian Federation, Azerbaijan, Kazakhstan and Turkmenistan) and two autonomous republics (Dagestan and Kalmykiya) began to harvest sturgeon in the Northern Caspian Sea. Despite efforts to establish regulations for sturgeon catch in the Caspian Sea basin, such an international agreement between the four former Soviet republics and Iran has not yet been signed.

Sturgeon poaching in the new states has increased dramatically. This is most damaging where sturgeon are taken illegally not only from rivers during the spawning period but also from the sea. The sea catch destroys stocks of young fish and makes no economics sense, because females caught at sea are not mature from caviar made of their roe is of very poor quality and cannot be sold officially on the international caviar market (Birstein, 1996).

According to estimates by Dieckmann & Hansen (the oldest caviar trading company in Europe) the total international market for caviar in 1995 was 450 million tonnes, whereas the legal production of caviar in the Russian Federation and Iran totalled only 228 million tonnes (Birstein, 1996). International caviar markets stimulate sturgeon poaching. Caviar lovers around the world gladly pay high prices for the delicacy.

TABLE 4. Sturgeon capture in the Caspian Sea (million tonnes)

Year	Russia	Kazakhstan	Azerbaijan	Turkmenistan	The former Soviet Union	Iran	Total
1900	22 800.0	0	5 100	1 100	29 000.0	0	29 000.0
1905	21 600.0	0	4 500	1 100	27 200.0	0	27 200.0
1910	18 400.0	0	3 800	900	23 100.0	0	23 100.0
1915	20 100.0	0	6 100	700	26 900.0	0	26 900.0
1920	1 400.0	0	1 500	0	2900.0	0	2 900.0
1925	8 000.0	0	3 700	400	12 100.0	0	12 100.0
1930	9 700.0	0	3 600	400	13 700.0	1 100	14 800.0
1935	9 400.0	4 100	4 000	1 800	19 300.0	840	20 400.0
1940	3 600.0	1 300	2 200	400	7 500.0	550	8 050.0
1945	1 500.0	300	1 700	100	3 600.0	620	4 220.0
1950	11 000.0	100	2 400	0	13 500.0	760	14 260.0
1955	7 500.0	700	2 200	100	10 500.0	710	11 210.0
1960	7 400.0	1 600	1 100	0	10 100.0	1 500	11 600.0
1965	10 600.0	3 900	400	20	14 920.0	0	14 920.0
1970	10 700.0	5 200	170	0	16 070.0	0	16 070.0
1975	14 670.0	8 250	34	0	22 954.0	1 500	24 454.0
1976	16 897.0	9 006	360	0	26 263.0	1 500	27 763.0
1977	16 610.0	10 413	340	0	27 363.0	1 500	28 863.0
1978	14 732.0	8 480	424	0	23 636.0	1 500	25 136.0
1979	15 181.0	8 936	535	0	24 652.0	1 500	26 152.0
1980	16 705.0	8 101	323	0	25 129.0	1 500	26 629.0
1981	17 217.3	7 635	319	0	25 171.3	1 496	26 667.3
1982	16 804.5	7 107	267	0	24 178.5	1 496	25 674.5
1983	17 013.7	6 539	224	0	23 776.7	1 500	25 276.7
1984	15 895.6	6 246	223	0	22 364.6	1 330	23 694.6
1985	15 062.6	5 895	241.9	0	21 199.5	1 650	22 849.5
1986	14 283.1	5 496	232	0	20 011.1	1 690	21 701.1
1987	14 972.0	4 090	185	0	19 247.0	1 690	20 937.0
1988	15 202.4	3 177	218	0	18 597.4	1 700	20 297.4
1989	13 431.8	2 269	120	0	15 820.8	2 051	17 871.8
1990	11 664.6	1 936.1	70.37	0	13 671.1	2 645	16 316.1
1991	8 547.5	1 767	108.6	0	10 423.1	3 036	13 459.1
1992	7 508.2	1 670	119.0	0	9 297.2	2 692	11 989.2
1993	4 238.1	1 109	240.5	0	5 587.6	1 710	7 297.6
1994	3 255.4	635	63.2	0	3 953.6	1 700	5 653.6
1995	2 301.8	562	43.4	180	2 907.2	1 500	4 407.2
1996*	1 779.0	510	24.0	0	2 313	1 360	3 673.0
1997*	2 044.0	460	23.0	0	2 527	1 200	3 727.0

Hamoonpad (1999), Ivanov and Majinic (1997).

*FAO statistics.

Thirty grams of Beluga caviar in the well-known New York store "Petrossian" sell for US$65, for example wheras the price of a kilogram of caviar on the black market in Moscow is US$250, (Birstein 1996).

United States Commerce Department data show that caviar imports has increased 100 percent since 1991. Meanwhile reputable caviar suppliers in Europe are being driven out of business by illegal trade. For example, from 1992 to the present the German caviar market has been overwhelmed by poor quality caviar (Birstein 1996).

Unique features of the fishery

The Caspian Sea and its sturgeon comprise a unique fishery. Among the various renewable and non-renewable resources naturally bestowed to the littoral states of the Caspian Sea, the sturgeon stocks are known worldwide, but they are very vulnerable to overfishing. During the last centuries, Russia has always been at the lead in terms of sturgeon fisheries around the world. Sturgeon have been fished in places other than the Caspian Sea, including Sea of Azov, Black Sea, Ural Sea, and a number of rivers in Siberia as well as in the far east, the Caspian Sea has always been the most exploited in this respect.

The sturgeon species are *Acipenserid chondrostans*, a primitive stock of teleost fish that diverged 200 million years ago (Berg, 1948 cited by Doroshov, 1985). Longevity is a characteristic of most sturgeon species and the Beluga can reach an age of over 100 years (Marti 1979 cited by Doroshov 1985).

Sturgeon includes two families: *Acipenseridae* and *Polyodontidae*, *Acipenseridae* includes 25 species in four genera such as *Huso*, *Acipenser*, *Scaphirhynchus* and *Pseudoscaphirhynchus*. They live around the world especially in the Caspian Sea, Black, Azov Sea and inland water. Twelve species are on the brink of extinction (Doroshov 1985, Birstein *et al.*, 1997, FAO 1999).

Sturgeon spends their adult lives in both freshwater and saltwater environments depending on the species. All of them however, migrate upriver to spawn. A relatively small number of species are truly anadromous. The most abundant group can be defined as semi-anadromous (Russian and Persian sturgeon, beluga, sevruga and ship sturgeon).

All sturgeon require a much longer time to reach sexual maturity and to complete the gametogenic cycle than most other fish. The average age of fish at their first spawning varies 10 to 25 years in different species (see in Appendix 2). All sturgeon species are iteraparous and spawn several times during their lives. Completion of one gametogenic cycle takes longer than one year. Intervals of two to eight years were indicated for sturgeon females (Doroshov, 1985).

RATIONALE FOR SEA RANCHING PROGRAMMES

Large brackish water seas, such as the Caspian Sea, provide unique conditions for sturgeon ranching due to their isolation from the ocean and an abundant food base. The major target of sturgeon management in the Caspian Sea is the capture of adult, sexually mature fish during the spawning migration and migration around the sea. Ripe fish are harvested from rivers deltas or lower reaches of rivers during their spawning migrations and used for caviar and flesh production. More than 65 percent of total spawning stock is removed by the fishery; the remainder is passed to those spawning grounds or artificial propagation in Russia (Marti, 1979 cited by Doroshov 1985).

Rationale for sea ranching

Sturgeon ranching was an attempt to mitigate for loss of sturgeon spawning habitat in rivers surrounding the Caspian Sea. Sturgeon migrates to river from the sea to lay their eggs. In the past, fishing used relied merely on natural recruitment of the sturgeon stocks. Rivers such as Volga, Ural, Kura, Sefidroud, Tajan, Gorgan and Atrak constituted some of the major natural spawning ground for these species. Destruction of natural spawning ground is one of the causes for the decline in the natural recruitment of the sturgeon stocks at present.

Obstructing rivers to control the discharge of water for agriculture purpose may bring about irretrievable losses of natural spawning ground of sturgeon. The discharge of water during springtime reduces the spawning potential of the sturgeon in Volga River (Khoroshko, 1972) and Aktoba River (Pashkin and Paletiva, 1992). Before construction of the dam on the Volga, sturgeon spawning ground area was as large as 3600 ha. Because of the construction of Volgagrad dam in 1958-1960 and of the storage reservoirs, 85 percent of the spawning grounds have been completely lost (Vlasenko, 1994; Birstein, 1996), about 3 percent of the spawning grounds are beyond backwater areas and only 12 percent have remained in lower Volga. According to the same report, all the spawning grounds for Belugas has been removed along with 70 percent and 40 percent for Russian sturgeon and Sevruga respectively (Vlasenko, 1994). More than 160 ha of natural spawning areas for sturgeon have been lost in Kura River followed by 132 ha on Tarak River and another 201.6 on the Sulak River. The only unregulated river flowing into the Caspian Sea is the Ural with the largest area (1 400 ha) of spawning grounds for sturgeons (Vlasenko, 1994). Therefore, building dams on these rivers has not only destroyed spawning grounds but flow depletion has changed the hydrological and hydrochemical regimes of rivers and the sea and reduced their biological productivity (Barannikova, 1991).

The Sefidroud, Gorganrud and Tajan rivers in Iran have lost their capacity to provide suitable grounds for sturgeon spawning in recent years because the rivers have been dammed (the Sefidroud dammed by three dams the Manjil, Tarik and Sangar). Due to drainage regulation during the spring season, the river usually becomes very shallow followed by severe fluctuations in water temperature downstream (Fadaee, 1997). Furthermore, creating dams on the Tajan River (Laloee, 1996), which is aimed at exploiting the water for agricultural purpose, as well as Voshmgir dam in Gorgan River have substantially impoverished these rivers in terms of their ability to support sturgeon migrations. All these factors have resulted in reduced water in the rivers.

Changes in the nature and location of principal sturgeons spawning grounds can be related to:

- human intervention of the inflowing waters of the Caspian Sea through the construction dams;
- industrialisation and irrigation;
- pollution of both rivers and the Sea from industrialisation and agricultural effluents;
- eutrofication resulting from the above;
- poaching and the destruction of immature fish through the use of non-selective gear, or inappropriate open seasons;
- inadequate fisheries management.

Evaluation of other sturgeon fishery management options

Fish season closure

When ice in the Volga and Ural rivers is melting, capture of sturgeon fishes begins in the mouth of Volga, Oral, Kura, Trek, and Solak rivers. At the end of winter and beginning of spring capture of sturgeon is carried out with common and specific beach seine (plates 26–28) in a special area of the Volga delta. Sturgeon capture is allowed prior to 15 May when the fish are migrating for spawning in the main branch of Volga except captures for research purposes or to provide enough broodstock for hatcheries. Sturgeon capture in this area is allowed from 15 May to 5 June. Fishing is not allowed in the basin in summer. Aurumn fishing in the Volga delta begins on 1 September and continues until the permitted annual catch level has been reached.

Sturgeon captures in the Ural River begins after ice-melt and are permitted between 25 May and 1 August again until the permitted annual catch level is reached. According to scientific advice, sturgeon capture stops after three days of fishing so that the broodstock can migrate through the river and then capture continues after two days.

Fishing time and methods in Iran are discussed in the section **Sturgeon fishing methods in the Southern Caspian Sea**. Fish season closure is under control of research centres and these do not permit capture of immature fish. These methods apply to capture of standard size fish.

The main problem in managing sturgeon stocks in all littoral countries is illegal fishing and it is not possible to control poaching. Iran has special guards who prevent illegal fishing at sea.

Restriction of fishing area

In term of fisheries improvement of sturgeon in 1960s, the Russian government decided to ban sturgeon fishing in the sea and switched to fishing in rivers. This action combined with artificial reproduction caused sturgeon catch to double in the late 1970s and early 1980s (Hamoonpad, 1999).

After prohibition of sturgeon capture in the sea, the Russian government limited fishing time and imposed high fines for illegal fishing. In 1994 the cabinet of the Russian Federation agreed to increase fines for any illegal capture of sturgeon fish to 35 percent, 14 percent and 12 percent of an offender's salary for beluga, ossetra, sevruga, respectively (Hamoonpad, 1999).

In an agreement between Iran and USSR in 1940, catch of sturgeon in Iran was permitted only in rivers and this was further agreed between Russian fishery committee and ministry of Jahad e Sazandegi in 1996. Iran's share of the sturgeon capture in the Caspian Sea was 10 percent of total capture and has undergone less damage.

In the mid 1970s Kazakhstan and the former USSR established a no-fishing area in the North Caspian Sea. Unfortunately, on 23 September 1993, the Kazakhstan government approved geological research activity and the extraction of hydrocarbon material from this area.

Restriction on fish gear in Iran

Sturgeon fishes were previously caught using longline method in which each vessel had 20 000-30 000 hooks with 25 hooks for every rope. This method was harmful to sturgeon stock because immature fish were trapped and killed. Therefore, capture methods changed to netting and variable mesh made from natural thread. Synthetic thread was bought from USSR in 1956 and all fishermen used these nets from 1963.

Before 1995 fin fish such as kutum (*Rutilus frisii kutum*) were caught with gillnets in the south of the Caspian Sea but studies conducted on this method have shown it was harmful to sturgeon stocks. Therefore, to preserve sturgeon stocks, in 1995 Iranian Fisheries spent US$25 000 000 purchasing all gillnet fishing permits. This fishing method was banned and not used in Iranian Fisheries (Pourkazemi and Hosseini, 1997). Iranian Fisheries decreased numbers of fishing vessels and fishermen from 430 to 343 and from 1 500 to 1 285 respectively from 1991 to 1998.

Sturgeon species inadvertently caught by cooperatives fishing for bony fish are obliged by law to report this to SHILAT officials, who are responsible for the disposal of the fish. In the 1994–1995 season, beach seine units in Gilan captured sturgeon weighing a total of just under 9 500 kg with caviar weighing 1 173 kg. In the following year the landing of sturgeon doubled to 21 800 kg to 2 259 kg of caviar.

Sturgeon fishing in the Volga River is with beach seine with a mesh size of 45 to 50 mm (knot to knot). Russia has enacted laws to decrease the accidental catch of sturgeon and encourages fishermen to return trapped fish to the sea in good condition (personal communication from KaspNIRK).

METHODOLOGY OF SEA RANCHING

Broodstock selection and management

The season of sturgeon breeding and fingerling production is restricted to the period from March to July in the hatcheries of the south Caspian Sea. Hatchery facilities are used at least twice during the breeding and rearing seasons. The most beluga sturgeon (*H.huso*) are caught in wintertime and the broodstock are kept to a suitable time for spawning. The beluga migrates to the Sefidroud River in early spring. Persian sturgeon and sevruga spawn in late spring and their fingerlings are stocked in May. The other species such as *A.stellatus* and *A.nudiventris* migrate to Sefidroud, Tajen, and Gorganrud Rivers.

Broodstock are caught in the rivers by beach seine and some of them are also selected from the fisheries stations around the rivers by experienced hatchery personnel. Large numbers of animals have to be captured and examined to obtain sufficient numbers of mature fishes that will spawn within a few months in captivity. They are examined by sampling eggs and a check of the germinal vesicle (GV), and if they are not suitable for injection they will be returned to the fisheries station for caviar processing.

In Iran broodstock captured in the rivers or sea are transferred to the hatcheries by truck equipped with oxygen (Abdolhay, 1996; Bradran Tahori *et al.*, 1997). The broodstock are transferred to ponds (75 × 12 m called a koransky) (Kohehshari *et al.*, 1974). The ponds have three parts, the first part is for long-term storage, the second part is for temporary storage and the third part is for injection of fish (Kohnehshari, *et al.*, 1974). In new hatcheries the broodstock are kept in earthen and concrete ponds (Abdolhay 1997).

The hatcheries in the Russian Federation are usually near navigable parts of the river. The broodstock are transported with special vessels (Abdolhay, 1997; Baradaran Tahori *et al.*, 1998). These vessels, called prolis, have numerous holes for the exchange of water between the river and the vessel (Abdolhay, 1996; Baradaran Tahori *et al.*, 1998).

The scheme of the hatchery enhancement cycle is shown in Table 5. Brood fish are selected from commercial landings and transported to the hatcheries. All fish are slaughtered after spawning. Progeny are raised in tanks or ponds until early or

TABLE 5. Sturgeon ranching scheme in the Caspian Sea (Iran and Russia)

Capture (Feb.–May)	Commercial fisheries in river deltas supply food markets with flesh and caviar and supply hatcheries with ripe broodstock.
Spawning (March–May) (3–5 days)	Ripe fish are induced to spawn via hormonal treatment. Broodstocks are slaughtered.
Egg incubation (5–10 days)	Eggs are incubated in jars or in trough incubators. Newly emerged larvae are held in circular tanks.
Fingerling production (40–60 days)	Fry are stocked and raised in fertilized ponds in tanks until fingerlings reach 3–5 g mean body weight.
Release (June–July)	Fingerlings are released in river deltas.
Capture (10–20 years)	Sexually mature fish return to the rivers for spawning and capture by fisheries. Their return to the fisheries is 1–3%.

Doroshov, 1985

midsummer, when juveniles reach 1 to 3 g body weights. These fish are released into river deltas or upper estuaries. Broodstock selection is earlier in Iran and they are often collected in winter. In-depth research on sturgeon embryology conducted by Detlaff and Ginzburg (1954) contributed to major improvements in sturgeon hatchery spawning and egg incubation techniques.

Reproduction (After Doroshov 1985; see plates 1–12)

Ovulation is recognised by the palpation of the female's abdomen or by the spontaneous discharge of a few sticky ova. A reasonable prediction of spawning induction response is possible through the examination of the germinal vesicle position. A rapid method to determine gonad maturity in the sturgeon is via the location of the GV. Follicles are removed with a probe and boiled in water for 2 minutes in a test tube and then are cut with a sharp safety razor blade exactly along the axis through the animal and vegetal pole and an index of oocyte polarization is then calculated.

Ripe fish are injected with ovulation-inducing substances. Gerbilsky (1972) established methods of induced spawning via the intramuscularly administration of acetone and dried pituitary glands. Sturgeon pituitary glands are used for the induction of ovulation and spermitation in Iran and in the Russian Federation. Glands are obtained from commercial sturgeon catch and stored after dehydration in acetone. Leutenizing Releasing Hormone, LRH-a synthetic analogue has also been used to induce spawning. The dosage of hypophysis and LRH depend to the weight of fish and temperature for each species (Dettlaff *et al.*, 1993; Shafizadeh and Vahabi, 1996). The collected eggs are fertilised with semen and diluted with hatchery water to avoid polyspermy (Kohehshari *et al.*, 1974; Dettlaff *et al.*, 1993).

To be successful, hypophysation requires the use of pituitary materials from suitable donor fish. The donor should be a mature pre-spawned fish, preferably of the same species as those that are to be spawned. Pituitary can be preserved in alcohol or acetone, but acetone-dried material is easier to handle. In order to preserve the glands, they should be placed in absolute acetone, which has been refrigerated or placed on dry ice. The acetone should be changed several times over a 24-hour period to ensure that the glands have been properly dried and deflated. They are then dried on filter paper or under vacuum and stored.

PLATE 1. Broodstock transfer

PLATE 2. Hormone injection

PLATE 3. Check ripping fish

PLATE 4. Remove eggs

PLATE 5. Remove ovarian fluid

PLATE 6. De-adhesion the egg

PLATE 7. Sperm collection

PLATE 8. Sperm addition

PLATE 9. De-adhesion of the egg by mixing

PLATE 10. Water hardening eggs with silt

PLATE 11. Transfer egg to the incubator

PLATE 12. Slaughtered fish

Two consecutive injections are recommended to obtain the best ovulatory response. The total dose for the female is divided into two injections, an initial dose of 10 percent and final dose of 90 percent. Male fish receive a single injection when the female has her second injection. In females, the gland extract is injected intramuscularly (between the lateral and dorsal scutes within the area extending from the base of pectoral fin to the midsection of the fish). The time between the last injection and ovulation ranges from 15 to 40 hours and depends on species and water temperature.

The following equipment is necessary for performing insemination: dry pans for eggs, dry vessels for the sperm, enamel-coated bucket, 100 ml measuring cylinder, microscope, several glass slides, a glass rod and a pipette. Ripe sperm are collected by stripping or by catheterization of male and sperm can be kept intact at refrigerator temperature for at least 24 hours prior insemination without any noticeable decrease in fertility (Doroshov, 1985). Before the sperm is used to fertilise eggs they are examined under a microscope to determine viability. Stripping of eggs is not feasible for most sturgeon because the structure of the female oviduct allows only partial stripping of small portions of ova. The eggs should therefore be removed by opening the female abdomen.

The eggs collected are fertilised by different established methods of insemination: dry, semidry and wet methods. Comparison of the effectiveness of these three methods of insemination was carried out on the eggs of *A. stellatus*. The best results were obtained with the semidry methods (Ginsburg, 1968) where the eggs and sperm are collected in dry containers, but shortly before addition to the eggs the semen is diluted by hatchery water at ratio 1: 200 to avoid polyspermic fertilization (Doroshov, 1985) because the sturgeon have many micropyles. Eggs have to be placed in a cool place and protected from direct sunlight. Insemination should be performed without delay, preferably no later than 10 to 20 minutes after collecting eggs.

Activated eggs become highly adhesive within a few minutes after fertilisation. In USSR, Derjavin (1914) developed a simple egg de-adhesion technique using silt coating of eggs immediately after insemination. For de-adhesion, the eggs are placed immediately after insemination into a suspension of clean silt (washed, dried and sieved to particles 10–20μm) and gently stirred for 20-40 minutes. Alternatively urea, tannic acid and various salts can be used instead of silt to remove chemically the jelly layer from fertilised sturgeon eggs; a treatment of urea and sodium chloride (NaCl) or sodium sulphide (Na_2SO_3) is followed by a tannic acid wash (Conte *et al.,* 1988). The silt method is used in Iran for de-adhesion of fertilised eggs.

Determination of the percentage of fertilisation and polyspermy are of great importance to fish culture and is carried out for all incubated batches of eggs at the 2nd cell division of the eggs. If the technique of insemination was correct, usually no more than 4–6 percent of polyspermic eggs are present in a batch of good-quality eggs (Dettlaff *et al.*, 1993).

Incubation (see plates 13–14)

The Russian hatcheries use Osetr incubators for egg incubation at present and they do not use the Yuschenko system (Abdolhay, 1996; Baradaran Tahori and Abtahee, 1998). The Osetr incubator has some advantages over the Yuschenko, such as greater capacity, higher efficiency and low noise. To reduce stress larvae transfer to the tank is done by water flow without contact by hand. Water flow also removes dead and diseased eggs (eggs with saprolegnia) automatically to prevent contamination to healthy eggs (Pourasady, 1995).

The most popular egg incubator in Iran is the Yuschenko trough, which was designed by Russian experts. The Iranian experts who were trained in Russia constructed an Osetr incubator system in Iran in 1996 (Pourasady, 1996). The period of incubation depends on species and temperature and is usually 7-12 days.

PLATE 13. Yuschenko incubator

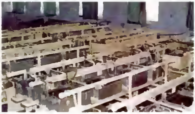


PLATE 14. Osetr incubator

Methods of larvae rearing (see plates 15–23)

Three methods of fingerling production are used in Russian and Iranian hatcheries.

- Rearing in earthen ponds from initiation of feeding to final fingerling size.
- Rearing in tanks on cultured live food up to or beyond metamorphosis, followed by additional grow-out in ponds until final size.
- Intensive tank culture.

The first method used on Volga River hatcheriesn is inexpensive and cost efficient but requires appropriate climatic conditions and pond management to produce predictable harvests. The larvae are stocked in ponds just prior to the initiation of feeding, at a density of 60 000 to 75 000 per hectare. Ponds (usually 2 ha surface and

PLATE 15. Transfer of the larvae to fibreglass tank

PLATE 16. Concrete tank for larvae

PLATE 17. Fibreglass tank for larvae

PLATE 18. Larvae rearing

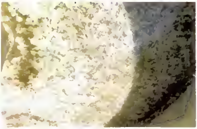


PLATE 19. Larvae rearing

PLATE 20. Pond rearing

PLATE 21. Fingerling collection

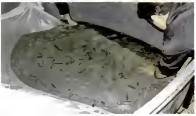


PLATE 22. Fingerling counting

2 m maximal depth) are fertilised with manure prior to and after stocking. The rearing period continues for 30 to 40 days. The survival at harvest is 50-60 percent and fingerling size is 2-3 g.

The second method (used at hatcheries on Kura River and in Iran) includes initial rearing in tanks to overcome the problems associated with the possible high mortality of larvae in the ponds. Between 20 000 and 30 000 larvae are stocked in each 2 m diameter, 30 cm deep round tank. Fry are fed the white worm (*Enchytraeus albidus*), zooplankton (*Daphnia* and *Moina* sp) and the brine shrimp (*Artemia* sp), that have been cultured in the hatchery. After reaching 0.1–0.3 g body weight, fry are stocked in fertilised ponds to complete grow-out. The survival in tanks is 50–80 percent and that in the pond is 70–80 percent (Milstein, 1972, cited by Doroshov, 1985).

PLATE 23. Fingerling transfer to a river in Iran

In Iran the concrete pond (2.5 m diameter and deep with a 30 cm, capacity of 30 000–35 000 larvae) and fiberglass tank (2 × 2 × 0.5 m with a capacity of 15 000–20 000 larvae) were constructed and aeration used to increase density in new hatcheries. Stocking the larvae to the pond will be done at 70–80 mg. This method is suitable for Iran because of low production of larvae to overcome the problems associated with the possible high mortality of larvae in the ponds. The survival rate in tanks, incubator and ponds is shown in Appendix 1 (Abdolhay and Tahori, 1997).

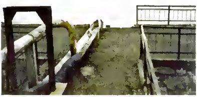
The third method is used when the number of larvae is very low and it is necessary to keep them in the small pond to reduce mortality. Sometimes this method is used in Iran, especially in autumn propagation season.

Larval rearing in ponds

The quality of pond soil will be tested in autumn. Five million tonnes of cow manure are added to the pond and water is added 10–15 days before stocking larvae. Initially, water depth is kept at 1 m and fertiliser is put in the pond (ammonium phosphate and ammonium nitrate). After the daphnia stock is added to the pond and water depth increased to 1.5–2 m, sampling is performed during rearing of fingerling and phytoplankton, benthos condition factor, growth rate and nutrition are monitored.

Most ponds are 1–2 ha in size; the stocking density is between 70 000 and 90 000 fry per ha, dependent on species and fertility of the pond. A project was established to increase stocking density by aeration. The stocking density was increased up to 200 000 fry per ha. The survival rate was increased from 50–60 percent to 85– 90 percent and the average fingerling production was increased from 50 000 to 100 000 per ha (unpublished data). The average body weight of fingerling is about 2–3 g for 30–40 days at which point they are released to the river.

PLATE 24. Fingerling releasing directly to the river in the Russian Federation



Release strategy

Three mechanisms for releasing fish are used:

- spot planting: introducing all the fish into the receiving waters at the same time
- scatter planting: introducing fish into several sites in the same region;
- trickle planting: introducing fish into the same region over a period of time (Cowx, 1994).

Spot planting can lead to competition among stocked fish, or with natural stocks and in rivers it is often associated with considerable downstream displacement to reduce population interactions. Scatter stocking gives a wider dispersal at the outset and minimises competitive pressures. Trickle stocking similarly removes competition but is often constrained by lack of labour, finance and available stock. Evidence suggests that scatter and trickle stocking (Berg and Jorgensen, 1994) are more successful than spot stocking but the latter is generally carried out because it is easier to undertake (Cowx, 1994).

In the hatchery centres of Astrakhan (the Russian Federation) sampling is carried out by trawlnet during release of sturgeon juveniles and an estimation of the approximate number of juvenile sturgeon is maintained. However, according to Russian experts, in order to obtain a more accurate account of the actual number of produced fingerlings, a more rigorous method of counting was used during the early years of operation. Nevertheless, in order to avoid manipulation stress on juvenile sturgeon, and because of the great number of rearing ponds, estimation of the released fingerlings is statistically done through applying trawlnet. After estimation the number of fingerling in each pond, they are directed toward the outlet channels that flow into the river. In order to enhance the survival rate of fingerling some of them are transported by special vessel to the feeding ground (Vlasenko, 1994).

As the sturgeon hatchery centres in Iran are located far from the rivers, the fingerling (3–5 g) are introduced into fish collectors by gradually draining the ponds and forcing the fingerling through concrete water canals. They are then counted in a special container and their average weight is determined.

The fingerlings are then transferred to the rivers by trucks that contain oxygen tanks, and are released into the rivers. Careful monitoring is carried out in terms of timing, location and the weight of fingerling in Iran; counting of the juvenile fish is performed by fisheries research officers. The fingerlings in Iran are usually released in rivers such as Sefidroud, Tajan and Gorgan that have abundant flow of waters. Meanwhile the fisheries research centres carry out certain studies on the migration of sturgeon (Fadaee, 1997).

PLATE 25. Boat for transfer of broodstock in the Russian Federation

Genetic resource management

The first step in conserving genetic resources is to determine what genetic resources exist. This basic information is often lacking or incomplete for many aquatic species. Protein or isozyme analysis enables the genetic variability of numerous species to be examined quickly and relatively cheaply. Protein variation can provide information on geneflow, population structure, species identification, taxonomy, hybridization, and evolutionary relationships in fishes. More information is becoming available on DNA level variation in aquatic species (Cited by Bartley, 1995).

PLATE 26–28. Capture of broodstock in the Volga River

In the conditions that existed after the Volga River flow regulations, the probability of interspecific mating of sturgeon increased. Sturgeon hybrids have accounted for 0.02–3.1 percent of the total number of migrating sturgeon juveniles over all the years for which data exist (Lagunova, 1997), the proportions of the different hybrids has varied with time. Between 1964 and 1981 the hybrid Russian sturgeon × sterlet (*Acipenser ruthenus L.*) was most common and accounted for 51.3 percent of all hybrids, Russian sturgeon × sevruga accounted for 28.2 percent and sevruga × sterlet accounted for 20.5 percent (Lagunova, 1997). From 1982 to 1994 the hybrid Russian sturgeon × sevruga was prominent and its percentage nearly doubled (55.7 percent) whereas the proportions of Russian sturgeon × sevruga decreased 1.5 times (to 33.9 percent) and the proportion of the sevruga × sterlet decreased to 10.4 percent. Different sturgeon hybrids have varied in number over all the period of observations in Volga River. It seems most likely that the increasing number of Russian sturgeon × sevruga was promoted by a reduction in spawning areas, together with improved reproduction conditions for the Russia sturgeon breeding in summer as a result of stored water releases during a period of low water period (Lagunova, 1997).

At present, the preservation of all sturgeon species cannot be guaranteed. Many are in very poor condition and may disappear in the near future. Rare sturgeon species are in dire need of genetic conservation. Within framework of the Russian Federation Committee of Fisheries (Goskomrybolovstvo) a long-term programme of Sturgeon Biodiversity Conservation was begun in 1990s. Live collections of rare sturgeons coupled with of sperm cryopreservation was suggested as a means to help in gene pool conservation.

The question is whether a long-term species-group raised in captivity can be based on a limited number of live specimens and a large amount of frozen sperm (Artyukin *et al.* 1997). Currently, within the framework of the programme, several special facilities for the central collection of live sturgeon are under construction near Moscow. A sperm bank was also created in a laboratory in St. Petersburg (Artyukin *et al.* 1997).

A gene bank for frozen sperm is planned in the Sturgeon International Institute in Rasth in Iran (Alipoor *et al.*, 1998).

The maintenance of rare sturgeon stocks in captivity began in the 1980s. In particular, a small population of Sakhalin sturgeon (*Acipenser medirostris* Ayers) was begun in Konakovo experimental hatchery, Tver region. Here the males started to produce sperm at the age of 6 years. The female Sakhalin sturgeon matured in Konakovo hatchery at age 9 years. Iran is also experimenting with a live gene bank at Beheshti hatchery in Rasht and in other inland areas (personal communication, Bahmani and Kazemei, 1998).

Iranian hatchery experts try to produce high quality and healthy fingerlings but with the mass production of fish it is difficult to give consideration to some aspects of genetic management. Hatchery managers try to keep separate broodstock for each area. No hybrid fish are released to the sea (Rezvani, 1990). Some projects have sought to produce beluga-sevruga, beluga-Russian sturgeon and ship-beluga, but this research is undertaken to obtain data on best growth rate for culture.

Fish health management

In the hatchery

With regard to the release of juvenile sturgeon, the health control laboratories have responsibility for monitoring the production process in different stage of the task within the hatchery centres. Through sampling and examining, they take the required measures in identification, control, prevention and elimination of the stresses or any other causes of disease that increase mortality in broodstock, eggs, or in the developing embryos incubators and finally among the newly developed fingerlings that are in earthen ponds. Such laboratories play an effective role in improving the quantity and quality of sturgeon for release (Jalali, 1998).

Monitoring includes medical examination of the transferred broodstock to hatcheries as well as growing fingerling up to release. Some of the main medical measures are: disinfecting the broodstock ponds, disinfecting of hatchery (i.e. incubators, larvae culture ponds), inspecting the received broodstock and disinfecting skin injuries, sterilising the soil used for de-adhesion of eggs, sampling the live food consumed by the cultured larvae, disinfecting the canals and waters remaining in ponds by splashing them with lime, combating the intermediate host of many parasites, and drying and disinfecting the ponds using lime (Personal observation).

Fingerlings are disinfected at different stages until release to ensure that problems are eliminated. Sampling is performed before the actual release of the fingerling as a final check. Macroscopic and microscopic examinations of the samples in the laboratory give final assurance about the broodstock. If there is any acute form of contamination or bacterial infection, the broodstocks are not use for reproduction.

In general, only few instances of contamination have occurred because all necessary control measures have been taken. In addition, the rearing ponds are only used for two months of the year and after which they are drained and lime is splashed on the ponds for disinfecting purposes. There is also a low density of fish in the ponds (80 000- 100 000 pieces per hectare) with no utilisation of artificial feed.

In the sea

Deterioration of the ecological situation in the Caspian Sea and its flowing rivers has been responsible for the degraded physiological state of sturgeons during their marine and river periods of life, which has manifested itself in metabolic disturbance, and impaired haematological blood characteristics. Histological investigations suggest severe gameto- and gonadogenesis disturbances in the sturgeon. Many specimens at gonad maturation stage II in their marine period of life display oocyte abnormalities. More than 30 percent of females migrating into rivers have reproductive products at the initial stage of resorption. In 1988–1989, water pollution gave rise to many cases of a disease of sturgeon in the lower Volga river, characterised by lamination of the muscle tissue and the egg membrane. Complete loss of the sturgeon stock has become a real possibility (Vlasenko, 1994).

MONITORING AND EVALUATION PROGRAMMES

Enhancement goals

Considering the high value of the sturgeon resources, the decline of the sturgeon stocks triggered the establishment of hatchery centres and fingerling release programmes in 1955 in the former Soviet Union that was followed by a similar trend in Iran in 1972. In 1950s, sturgeon hatchery centres were established along the Volga River with the aim of improving sturgeon stocks. In 1954, the Koorinski hatchery started operation followed by Kizaneski hatchery in 1955 (Ivanov and Majinic, 1997).

TABLE 6. Sturgeon hatchery programme in the Russian Federation and Azerbaijan

Reproduction hatchery	Pond area (ha)
the Russian Federation	
Kizaneski	124.5
Bertoleski	165.0
Alexanderofski	175.3
Jinefnski	129.0
Sergiofski	100.0
Libiaji	292.5
Eikrianensko	59.0
Volgagradski	117.9
Plavzavod	-
Total hatchery in Volga	1163.2
Sulakski	26.0
Treski	91.3
Total in Daghestan	117.3
Total hatchery in Russian Fed.	1280.5
Azerbaijan	
Ust koorinski	86.1
Ali bairaminski	42.0
Kora experimental reproduction hatchery	21.3
Total hatchery in Azerbaijan	149.4
Total	1429.9

Ivanov cited by Hamoonpad (1999).

The carrying capacity of sturgeon in the Caspian Sea has been estimated at 50 000 million tonnes, but the harvest was only 29 000 million tonnes during the 1900s. The capacity of the Caspian Sea with regards to food supply permits an increased release of juvenile sturgeon up to 150 million one-summer-old fish (Vlasenko, 1994; Ivanov *et al.*, 1997). With the emergence of hatchery centres in Russia, the capacity reached 27 000 million tonnes. There are currently 11 hatchery centres in the Russian Federation along with five and three in Iran and Azerbaijan respectively (Tables 6 and 7).

In the second development plan of Iran, the construction of hatcheries began with the aim of producing 14 million sturgeon fingerling. With the construction of new hatchery centres along with an increased expertise, and training provided by Russian fishery experts, the production rate of sturgeon fingerling which was lower than one million individuals in 1981 rose to 24.5 million individuals in 1998 (Abdolhay, 1997). The sturgeon hatchery

TABLE 7. The sturgeon hatchery programme in Iran

Hatchery name	Total area (ha)
Beheshti	110
Siahcal	210
Marjani	45
Rajai	77
Woshmgear	300
Total hatchery in Iran	742

Abdolhay (1997).

area was 72 ha in 1981 and increased to 742 ha in 1997 (Table 7). The development programmes are still underway. Fingerling production decreased from 1981 to 1986 (less than 2 million) as a result of production of Chinese Carp and kutum (*Rutillus frissii kutum*). Fingerling sturgeon production in Siahcal began in 1988 with 134 ha ponds, in Shahid Marjani in 1988 with 30 ha and in Shahid Rajai hatchery with 40 ha in 1995. Woshmgear hatchery began in 1996 with 144 ha ponds. (Table 7).

Enhancement goals for the Iranian Fisheries Company of Iran are the production of 50 million fingerlings and an increase in weight of fingerlings (up to 30 g), with an emphasisis on Persian sturgeon. Every year several million sturgeon fingerlings are produced and then released at the rivers. Table 8 illustrates the production and release rate of fingerlings in both Iran and the former USSR. Hatchery activities began operation with an annual production of 2.6 million fingerlings in Russia in 1955. This increased in 101 million fingerlings in 1985, and since then has followed a falling trend, to such an extent that the former USSR produced only 55 million fingerling in 1996 (Artyukin *et al.*, 1997; Ivanov and Majinic, 1997; Hamoonpad, 1999).

TABLE 8. Sturgeon fingerling release to the Caspian Sea (millions)

Year	Russia	Azerbaijan	Kazakhstan	Total	Year	Iran
1955	0.84	1.73	0.02	2.59	1960	0.0
1960	2.81	5.52	0.63	8.96	1965	0.0
1965	30.15	10.91	1.21	42.27	1970	0.0
1970	39.82	15.30	0.61	55.73	1972	1.60
1975	56.87	19.87	0.54	77.28	1975	3.90
1980	65.58	19.92	–	85.50	1980	3.03
1985	82.88	17.96	0.63	101.47	1985	1.29
1990	75.88	17.55	0.76	94.19	1990	4.55
1991	72.29	9.14	–	81.43	1991	6.59
1992	75.06	2.97	–	78.03	1992	3.45
1993	62.90	2.39	–	65.29	1993	4.17
1994	68.96	1.57	–	70.53	1994	5.91
1995	55.66	1.24	–	56.90	1995	9.12
1996	51.059	4.06		55.65	1996	12.45
1997					1997	21.62
1998					1998	24.55

Ivanov and Majinic (1997), Abdolhay (1997) and SHILAT for current estimates.

Measures of success and contribution of hatchery fish to fishery

Young sturgeons of the Volga-Caspian region have been reared at hatcheries for over 40 years. However accurate evaluation of the effectiveness of sturgeon culture presents certain difficulties. Wild spawning is still greatly effected by anthropogenic "pressure". Attempts to tag hatchery-produced young fish to distinguish between them from wild fish have not been successful. Several investigations observed that some sturgeon fry had a morphological anomaly of the nasal capsule: a complete or partial absence of septum between olfactory orifices. Such fry are quite numerous among hatchery-produced fish but are uncommon among wild fish. This anatomy is retained by the fish throughout their lifetime and can be used as "a natural mark" to estimate the coefficient of commercial return. In 1985–1986 and 1988–1991 the proportion of Russian, beluga and stellate sturgeon with such "marks" among the fish reared at Astrakhan hatcheries was determined to range from 0 to 77 percent. The percentage is usually higher among stellate than Russian and beluga sturgeons (Podushka and Levin, 1993).

The Russian Federation

There was previously no effective technique available for marking sturgeon fingerlings. The survival of hatchery fish was, therefore, monitored by periodic observations of their year-class strength in the sea. Because natural mortality is low in fish older than one year and fishing mortality in the sea is absent, the survival of hatchery recruitment is determined as the proportion of fish surviving until one-year of age in the sea. These estimates are primarily for beluga because natural recruitment is either absent or can be ignored for this species. Between 1960 and 1970, Soviet hatcheries released about 17 million beluga fingerlings annually. During that time the abundance of the first three year-classes of the beluga in the Caspian Sea increased tenfold compared with the period when only natural recruitment was available (Marti 1979, cited by Doroshov, 1985).

TABLE 9. Study of natural spawning in the former Soviet Union

Year	Catch (1000 million tonnes)	Natural spawning area (ha)
1959–60	7.5	450
1961–65	6.5	440
1966–70	6.0	430
1971–75	4.8	403
1976–80	4.5	376
1981–83	3.6	350

Moghim *et al.* (1996).

Over the last 30 years there has been some change in the species composition of the catch as a result of environmental stresses. The portion of Russian sturgeon has decreased from 70.6 percent in 1962 to 66.2 percent in 1995, for the sevruga from 29.1 percent to 26.8 percent, whereas the proportion of beluga has increased from 0.3 percent to 7.0 percent. The increased relative number of beluga is a result of its rearing on fish farms because the rate of natural reproduction of the beluga is very low (Ivanov *et al.*, 1997). As an average the survival of hatchery-produced fingerlings to the commercial fisheries is estimated at 1 to 3 percent.

The natural spawning of Russian sturgeon was at a maximum before damming of the Volga river. The fisheries return has been 7 500 million tonnes. The average percentage of natural spawning has decreased from 1961 owing to destruction of natural spawning ground (Table 9). Fingerling production has increased year by year in hatcheries. The annual production increased from 0.7 million in 1951-1955 to 45.5 million in 1981-1983. Studies of the effect of releasing fingerlings have been done by trawl survey and capture one-year classes of fish. Table 10 shows the annual fingerling production and captures by trawl.

TABLE 10. Study of fingerling release in the former Soviet Union

Year	Fingerling release (millions)	No. (100 in trawl)
1948–50	0.0	37.6
1951–55	0.7	22.8
1956–60	4.9	21.6
1961–65	11.2	53.0
1966–70	13.1	37.6
1971–75	23.1	22.8
1976–80	32.3	21.6
1981–83	45.5	53.0

Moghim *et al.* (1996)

Iran

Sturgeons are caught at 50 stations in the south of the Caspian Sea in Iran with numbers varying dependent on the station. All stations record the catch composition. Thirteen thousand fish are studied every year. Factors recorded are: species, fork length, total length, weight, sex, maturation stage, caviar weight, type of caviar and fish age. The age is determined by the first hard ray pectoral fin in the laboratories. Maturation is determined as described earlier. The total catch is measured every year and reported as catch per unit effort (CPUE) (Moghim and Ganinejad, 1994). Table 11 shows the catch composition of sturgeon species and Table 12 shows the catch composition of Ossetra (*A. guldenstadti, A. persicus and A nudiventris*) in Iran.

TABLE 11. Variation in catch composition of sturgeon in Iran

Year	Catch (kg)	Sevruga (%)	Ossetra (%)	Beluga (%)
1972	2 163 132	34.0	36.3	29.7
1994	125 872	49.5	41.0	9.5
1997	905 087	35.8	54.3	9.9

Abdolhay (1997), Moghim *et al.* (1996)

In the past, many fish were marked by the cutting the first hard ray of pectoral fin; some of them have been caught but not enough to provide meaningful information. In 1999, Iranian experts implemented a project for tagging the sturgeon fish. Reportedly Russian tags have been retrieved on sturgeon taken from the Caspian Sea in Gilan Province (personal communication with Razavi Sayad in Fisheries Research centre, Bandar Anzali, Gilan province, Moghim, 1992).

TABLE 12. Variation in catch composition of sturgeon in Iran (Ossetra species percent)

	1971–72	1989	1990	1991	1992	1993	1994	1995
A. goldenstadtii	89.6	50.2	42.2	40.0	36.7	34.7	29.0	26.6
A. persicus	4.2	44.2	53.8	57.0	60.2	62.3	68.2	70.6
A. udiventris	6.2	5.6	4.2	3.0	1.0	3.0	2.8	2.8

Moghim *et al.* (1996)

Economic analysis

No recent papers concerning economic analysis on Russian stocking are available. In Iran the study of the economics of the fishery has not yet been completed. According to the finance office in Shilat the cost for each fingerling is:

Operating cost	US$0.20
Capital cost	US$0.10
Caviar as egg	US$0.15
Miscellaneous	US$0.05
Total	US$0.50

The high cost of caviar as a source is an important case for fingerling production. One female of ossetra (standard size) may have 5 kg caviar that could produce 20 000 fingerlings (3–5 g).

Export, income and production of caviar are in Table 13 from 1989 to 1999. Prices of caviar increased from US$192 per kg in 1989 to US$312 per kg in 1998, US$385 in 1999 and over US$500 in 2000. Production decreased from 209 million tonnes in 1989 to 126 million tonnes in 1998 and was about 100 million tonnes in 1999 (Hosseni, 1997, personal communication).

TABLE 13. Export of caviar and income in Iran

Year	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Income (million US$)	40	52	54	42.2	30	30	41.5	40	34	39	34
Caviar export (tonnes)	209	251	225	169	167	156	146	100	106	126	90
Average prices (US$ per kg)	192	204	239	250	185	190	385	430	324	312	385

Interaction with natural population

Recent reviews demonstrated that many anadromous salmonoid populations are well adapted to their native habitat and that infusion of exotic genes from populations from different habitats, including hatcheries, may harm native fish (Hindar *et al.*, 1991; Waples 1991, cited by Bartley 1995). Some of the reported effects of the interaction between hatchery fish and closely related or conspecific fish are genetic erosion (loss of alleles), introduction of poorly adapted genes, introduction of disease organisms, changes in genetic subpopulation structures, changes in stock size, reductions in survival, changes in adaptive behaviour, reductions in homing accuracy, changes in migration patterns, reductions in recapture rate and increased disease susceptibility. Moreover, the effective size of an enhanced population could theoretically be reduced by the addition of hatchery fish with variable reproductive success and reduced genetic variability. The above effects are a result of direct competition, predation, and disease transmission between hatchery and wild stocks, as well as to the introgression of "hatchery" genes into the wild population (Bartley 1995).

However, the goal of many enhancement projects is for the hatchery and wild fish to mix and form a new and larger mixed population (Bartley, 1995). Therefore, trying to create fish in the hatchery that are compatible with wild stocks and the environment will be an important option for certain enhancement programs and for certain aquatic species (Bartley, 1995).

Natural reproduction of all three sturgeons species in the Volga River has been completely destroyed. Nearly all of the sturgeon migrating to the spawning grounds below the Volgagrad dam in 1995 are caught by poachers somewhere between Astrakhan and Volgagrad (Caspian Fishery Research Institute in Astrakhan, pers. comm). The hatchery in that area could not catch enough breeders for artificial reproduction of the sturgeon.

Because of the long time maturation of sturgeon, the impact of the interaction between wild and hatchery fish is difficult to assess. However, in the Caspian Sea, it appears that there are very few naturally produced sturgeon.

GENERAL CONCLUSION

General lessons

The major aim of sturgeon management in the Caspian Sea is the capture of adult, sexually mature fish during the spawning migration and migration around sea. In Iran and other littoral countries, the time from the initial stocking of fingerlings to fishery return is 10–20 years, far longer than in other aquaculture ventures. All commercial fisheries for sturgeon in the sea has been banned since the 1960 (Doroshov, 1985) and only Iran catches fish in deltas of rivers by gillnet. After the break up of the Soviet Union three new littoral countries also collect sturgeon.

Mention has been made of the introduction of sturgeon juveniles and fingerlings of other species into the Caspian Sea to enhance and safeguard the resource.

Although Iran began this practice in 1972, Shilat has undertaken a progressive stock enhancement programme since 1983 when 1.03 million juvenile sturgeons were released. Since that time the annual production and release of fingerlings has increased rapidly. In Iran, 3.46 million sturgeons alone were released into the Caspian Sea in 1992 and 24.5 million in 1998. It is possible to develop fingerling production because of good knowledge, pond area available and support of the Iranian government for investment. However, cooperation among the five littoral countries is necessary to provide management for sustainable fisheries. After dissolution of the USSR in 1991, fishing pressure increased, with substantial illegal fishing. Most natural spawning areas have been destroyed. In light of this, artificial reproduction has an important role for increasing sturgeon stocks in the Caspian Sea.

Strengths and weaknesses of the programme

Natural spawning plays a major role in the preservation of genetic structure of the population and the genetic diversity of the sturgeon stocks. Alteration at rivers, however, caused by dams creates dire ecological situations for the Caspian Sea. Fortunately, there are still some rivers that offer inviting conditions for natural spawning.

Artificial breeding and production aimed at stock rehabilitation plays a crucial part in this respect. According to KaspNIRKH (Caspian Fisheries Research Institute, Astrakhan), the contribution of stocked fish of various sturgeon species in the sturgeon fishery are 90 percent for beluga, 60 percent for ossetra, and 50 percent for sevruga (Ivanov and Majinic, 1997) whereas stocking constitutes 100 percent of Persian sturgeon recruitment (Abdolhay and Baradan Tahori, 1998). With the availability of nearly 2000 ha of ponds in the Russian Federation, Iran and Azerbaijan, along with the knowledge and expertise in those countries, it may be possible to revive the sturgeon resources through artificial breeding of these species.

During recent years overfishing has inflicted great damages to sturgeon stocks. Devastation to the natural spawning grounds has also been important. The collapse of the former Soviet Union has negatively affected the economic and social status of the newly independent republics, and coastal inhabitants in these countries have done great damage to the fishery resources. The lack of appropriate exploitation and fishing management system in the newly independent republics, the discharge of pollutants into the sea, lack of control, monitoring and surveillance on fishermen, and oil extraction operations have all together jeopardised substantially the future of the sturgeon stocks.

Some of the problems with hatchery practices are:

- lack of control and survey on the status of the released juvenile sturgeons and their return rate;
- lack of economic assessment of the artificial breeding costs and its economic impact;
- lack of knowledge about the available genetic stocks of the Caspian Sea and the difference between various species and groups in order to avoid genetic complications.

Future prospects and limitations

On the basis of many years study on the nutrition of food relationships of fishes of the Caspian Sea, Shorygin (1952) proposed the idea of converting the Caspian Sea into a predominantly sturgeon waterbody. The theoretical basis for reconstruction of the food base of sturgeons was developed in the Caspian Sea and *Syndesmia* and *Nereis* were introduced from Azov Sea into the Caspian Sea. These two species constitute about 70 percent of the reserves of variable prey organisms, whose biomass has increased more than three times (Barannikova, 1988). However, at present there are no plans for introducing or increasing the prey species into the Caspian Sea.

Currently, sturgeon broodstock are killed during egg extraction. It may be possible to remove eggs surgically without sacrificing the adults, thus allowing further reproduction (Podushka, 1997).

Given the decrease in mature sturgeon, it is necessary to reconstruct and to build facilities for long-term storage and culture of sturgeon broodstocks. At the same time, it is advisable to revise the standards of fish production towards increase of sturgeon fry weight at release up to at least 10–15 g; in particular, it should be carried out at fish farms of Dagestan, Azerbaijan, and Iran (Kokoza, 1997). Means to protect young sturgeon on feeding grounds need to be developed.

The Caspian sturgeon stock has been so devastated that sturgeon commercial fishery may be banned in the near future, with the catch of sturgeon only for research and artificial breeding purposes. Nevertheless, sturgeon conservation and restocking is still possible. A solution to this problem should be the concern of all the Caspian states (Ivanov *et al.*, 1997) because illegal fishing is still continued by some of these countries.

In 1991, after the dissolution of the USSR, the Caspian States, which include Iran, the Russian Federation, Kazakhstan, Turkmenistan, and Azerbaijan, guaranteed "the fulfilment of international obligations arising from treaties and agreements of the former USSR". In that same year, the Russian Federation proposed a multilateral programme for conservation of biological resources, which would introduce fishing quotas and mandatory fishing regulations, and include the original exclusive fishing zone. The most important step to save the Caspian sturgeon must be the immediate signature of "The agreement of the conservation and use of bioresources of the Caspian Sea" by the Russian Federation, Kazakhstan, Azerbaijan, Turkmenistan, and Iran and its implementation by each of five bordering states (Lukyanenko *et al.*, 1997). A substantial increase in sturgeon stocks is also attainable in near future, provided that the littoral states of the Caspian Sea pay due attention to the agreement prepared by experts and take the required measures to preserve the bioresources of the Caspian Sea. The agreement has been the object of permanent interstate negotiations for several years. (personal communication from international office of the Iranian Fisheries). Concern for sturgeon conservation was already expressed under the project "agreement on Caspian Bioresources Conservation and Management", which was designed by representatives of all states bordering the Caspian Sea: Azerbaijan, Kazakhstan, Iran, the Russian Federation, and Turkmenistan (Ivanov *et al.*, 1997) but this has yet to be signed.

The Caspian sturgeon conservation problems were discussed at a conference with the president of the Russian Federation B.N. Yeltsin present at the Astrakhan meeting in 31 October, 1992, when the president's Directive No 642-rp "On Measures for Caspian Sturgeon Conservation" was signed. Subsequently, the Directive No. 28-r was issued by the Prime Minister of RF VS. Tchernomyrdin on 29 January, 1993. According to these documents, a long-term programme on sturgeon reproduction, conservation and restocking was to be developed by specialists of the state Fishing Committee in collaboration with experts of the Russian Academy of Science, Ministry of Ecology and Ministry of Science, this has so far been partially implemented (Ivanov *et al.*, 1997).

Islamic Parliament of Iran proposed severe punitive measures against illegal fishing of sturgeon for the protection of marine resources. In 1992, Iran followed Russian suggestions with a proposal to establish a framework for cooperation through a regional organization. This was to regulate all aspects of the utilisation of the Caspian Sea and its resources. Such an organization was to:

- develop a database management and geographic information system to permit ease of rational control and transfer of diverse information between the Caspian States;
- establish conservation areas;
- formulate social and economic programmes to enhance conservation measures;
- encourage ways and means to promote these;
- monitor and predict sea-level fluctuations and the effect of river control upon the ecosystem;
- introduce programmes for the rehabilitation of affected endangered species and habitats;
- improve fisheries management and so safeguard this resource for the benefit of all peoples of the Caspian States.

CITES (Convention on International Trade in Endangered Species)

Following several international meetings on trade and illegal fishing in June 1997 (in Harare, Zimbabwe) the tenth meeting of CITES listed all sturgeon and paddlefish on Appendix 2 based on proposals submitted by Germany and United States. However, if the current downward trend in landing still continues, sturgeon fishing may be prohibited, which will require a collective approach by the coastal states of the Caspian Sea to prevent illegal fishing.

CITES listing will not only result in better international monitoring of the sturgeon trade but also enhance controls on the products in trade and ensure that sturgeon products, that are not traded in full compliance with provisions of the convention, can be confiscated or seized. In all major import markets of sturgeon products stiff penalties exist for CITES infraction and this has reduced illegal fishing. Anyone wishing to export caviar requires a CITES certificate and no one has been able to purchase more than 250 g of caviar from airport shops since 1998 (Hoseini, Director of Iranian Fishery Trade Company).

International Research Institute for Sturgeon

An International Research Institute for Sturgeon has been established in the grounds of Shahid Beheshti hatchery in Gilan Province in Iran. The objective of the Institute is the conservation and study of natural stocks of sturgeon in the Caspian Sea and inland waters. The Institute has departments planned for Biology, Nutrition, Reproductive Physiology, Genetics, and Fish Processing, and plans to work on Stock Assessment with other colleagues in IFRO (Iranian Fishery Research Organization). The projected complement of staff is 47, with 16 professional scientists.

The International Research Institute for Sturgeon, as the singlemost prominent fisheries body responsible for scientific investigation and research studies on sturgeon resources in Iran, began its operation in 1996. The actual research operation on various aspects of sturgeon resources started through the assistance of Russian research scientists from the KaspNIRKH institute as well as other senior experts.

The Institute currently has well-equipped laboratories and is in close cooperation with a number of research centres and universities in Iran as well as university students who are examining problems affecting sturgeon resources.

ACKNOWLEDGEMENT

Special thanks to Devin Bartley for assistance with editing this paper.

In regards to country names, the editors have used the Union of Soviet Socialist Republics for references to information prior to 1993 and used the Russian Federation after 1993 which refer to that specific former republic. With historical references it was often difficult to know which designation to use and no political statement or intent should be inferred.

References

Abdolhay, H. 1993. *Report of visit Russian fisheries.* Tehran, KaspNIRK in Astrakhan, Iranina Fisheries, International Office. (In Persian)

Abdolhay, H. 1996. *Report of visit sturgeon hatchery in Russia.* Tehran, Astrakhan, Iranian Fisheries, International Office. (In Persian)

Abdolhay, H. 1997. *Artificial reproduction of fish for stock enhancement in the Caspian Sea.* Seventh Conference of Shilat, Responsible fisheries, 17–18 February, pp. 187–207. Tehran, Iranian Fisheries. (In Persian)

Abdolhay, H. & Baradaran Tahori, H. 1998. *Review of reproduction of sturgeon from 1991–1997 in Iranian hatchery.* First National Symposium on Sturgeon, Rasht, 15–16 December. (In Persian)

Alipoor, A., Baradaran Noveiry, S. & Pourkazemi, M. 1998. *Sperm cryoperservation of five species of sturgeon.* First National Symposium on Sturgeon, Rasht, 15–16 December. (In Persian)

Amini, G.H., Matinfar, A. & Razavi, B. 1995. *Aquaculture status and development requirements in the Islamic Republic of Iran.* Tehran, Iranian Fisheries Research Organization.

Artyukin, N., Branannikova, I.A. & Romanov, A.G. 1997. Main feature of conservation and reproduction of sturgeons in Russia including the are endangered species. *J. Applied Ichthyol.*, 15: 1–352.

Artyukin, E.N. & Zarkhua, Z.G. 1986. R voprosu o taksonomicheskom rage osetra reki rion. *Vopor ikhtiol*, 26: 61–67.

Bahmani, M. & Kazemi, R. 1998. Histological study on the gonads of reared sturgeon. *Iranian Fisheries J.*, 1: 1–16.

Baradaran Tahori, H. & Abtahee, B. 1998. Comparison of sturgeon fingerling production between South and North of Caspian Sea. *In* I. A. Barannikova, ed. *Review of sturgeon farming in Soviet Union*, pp. 62–71. Scripta technical.

Barannikova, I.A. 1991. *Peculiarities of interapopulational differentiation of sturgeon (Acipenser guedenstaedti Brandt) under present-day condition.* P. Wiolliot, ed. Cemagref National Centre.

Bartley, D.M. 1995. *Marine and coastal area hatchery enhancement programmes.* International conference on sustainable contribution of fisheries to food security, Kyoto, Japan, 4–9 December.

Belyaeva, V.N. 1932. Osetr (*Acipenser gueldenstadti*) by ulleten vsekaspilskoi mauchoni rybokhoz vaistremoi ekspeditssi. *In* J. Holcik, ed. *Freshwater fishes of Europe*, Vol. 1, part 2, p. 161. Wiesbaden, Germany, AULA Verlag.

Belyaeva, V.N. 1972. Contributions and further directions of the research on sturgeon management. *Tzentr. Nauchno-issled. Inst. Osetr. Rybn. Khoz., rudy*, 4: 5–13.

Berg, L.S. 1933. *Fresh water fishes of USSR and adjacent countries.* Moscow, Nauka.

Berg, L.S. 1948. On the position of the Acipenseriformes in the system of fishes. *Zoo. Inst. Trudy*, 7–57.

Berg, S. & Jorgensen, J. 1994. Stocking eel (*Anguilla anguilla*) in streams. *In* I. G. Cowx, ed. *The rehabilitation of freshwater fishes*, pp. 314–325. Oxford, UK, Fishing News Books, Blackwell Scientific Publications.

Birstein, V.J. & Vasiliev, V.P. 1987. Tetrploid–octaploid relationships and karyological evolution in the order Acipenseriformes (Pisces). Karyotype, nucleoli, and nucleolus-organizer regions in four acipenseridae species. *Genetica*, 72: 3–12.

Birstein, V.J. 1993. *DNA content in Acipenseriformes species and the problem of chondrostan phylogeny.* International Symposium on sturgeon, 6–11 September. Moscow, Kostroma.

Birstein, V.J. 1996. Sturgeons may soon disappear from the Caspian Sea. *Russian Conservation News*, Spring: No. 7.

Birstein, V.J., Doukaakis, P. & DeSalle, R. 1997. Molecular phylogeny acipenserinae and black caviar species identification. *J. Applied Ichthyol.*, 15: 1–352.

Borezenko, M.P. 1942. *The Caspian sturgeon No. 7.* Baku, IZV Azerbaidzhansk. Naucho. Issl. Rybokoz. Stantsii. 114 pp.

Conte, F.S., Doroshov, S.L., Lutes, P.B. & Strage, E.M. 1988. Hatchery manual for the white sturgeon, *Acipenser transmantanus* Richardson. *Cooperative Extension University of California, Division of Agriculture and Natural Resources. Publ.*, 3322: 104 pp.

Cowx, I.G. 1994. Stocking strategies. *Fisheries Management Ecol.*, 1: 15–30.

Derjavin, A.N. 1914 Artificial reproduction of sturgeon and salmon in Kura River. *In* J. F. Muir & R. J. Roberts, eds. *Biology and culture of sturgeon, Acipenseriformes on recent advances in aquaculture*, Vol. 2, pp. 251–275. Westview Press.

Dettlaf, T.A. & Ginzburg, A.S. 1954. Embryonic development of sturgeon (in connection with problems of artificial propagation). *In* J. F. Muir & R. J. Roberts, eds. *Biology*, Vol. 2, pp. 251–275. Westview Press. 224 pp.

Dettlaff, T.A., Ginsburg, A.S. & Schmalhausen, O.I. 1993. *Sturgeon fishes: development biology and aquaculture.* Berlin, Springer-Verlag. 300 pp.

Doroshov, S.I. & Binkowski, F.P. 1985. *A perspective on sturgeon culture.* Symposium on Biology and Management of sturgeon. Annual Meeting of the American Fisheries Society, Milwaukee, WI, USA, pp.16–20.

Doroshov, S.T. 1985. *Biology and culture of sturgeon, Acipenseriformes on recent advances in aquaculture*, Vol. 2, pp. 251–275. Westview Press.

Fadaee, B. 1997. *Study of fingerling release in Sefisrud River to reach in sea in Iran.* Tehran, Iranian Fisheries Research Organization. (In Persian)

FAO. 1999. *Fishstat Plus Version 2.0.* Rome, FAO.

Faraji, M., Razavian, M. & Moshiri. 1995. *Geographical study of Gilan Fisheries Province.* University of Gilan, Rasht Iran. (In Persian) (M.Sc thesis)

Fejellheim, A., Raddum, G.G. & Saegrov, H. 1994. Stocking experiments with wild brown trout (*Salmo troutta*) in two mountain reservoirs. *In* I. G. Cowx, ed. *The rehabilitation of freshwater fishes*, pp. 268–279. Oxford, UK, Fishing News Books, Blackwell Scientific Publications.

Fontana, F. 1976. Nuclear DNA content and cytometry of erythrocytes of *Huso huso L., Acipenser sturio L.* and *Acipenser naccarii* Bonapart. *Carologia* 29: 127–138.

Gerbilsky, N.L. 1972 Biological foundation and methods of artificial reproduction on sturgeon. *In* J. F. Muir & R. J. Roberts, eds. *Biology and culture of sturgeon, Acipenseriformes on recent advances in aquaculture*, pp. 251–275. Westview Press.

Ginsburg, A.S. 1968. *Fertilization in fishes and the problem of polyspermy.* Moscow, Nauka. (In Russian)

Hamoonpad. 1999. *Exploiting from Caspian Sea by littoral country.* Tehran, Iranian Fisheries Research Organisation.

Holcik, J. 1989. *The freshwater fishes of Europe*, Vol. I, part 2, *General introduction to fishes Acipenseriformes.* Wiesbaden, Germany, Aula-Verlag.

Hosseni, M.R. 1997. *The end of irresponsible catching of sturgeon.* Seventh Conference of Shilat. Responsible fisheries, Iranian Fisheries, Tehran, Iran 17–18 February, pp. 115–129. (In Persian)

Ivanov, V.P & Majinic, I.U. 1997. *Fisheries activities in Caspian Sea basin.* KaspNIRKH. (In Russian)

Ivanov, V.P., Vlasenko, A.D., Khodorevskaya, R.P. & Raspopov. 1997. Contemporary status of the Caspian sturgeons (Acipenseridae) and the problem of the conservation. *J. Applied Ichthyol.*, 15: 1–352.

Jalali, B. 1998. *Parasite of fresh water in Iran.* Tehran, Iranian Fisheries Company. (In Persian)

Karataeva, B.B., Lukyanenko, V.I. & Terentev, A.A. 1971. Materialy kopredeleniyu populysatsionnoi struktury kaspiiskol belugi. *In* J. Holcik, ed. *Freshwater fishes of Europe*, Vol.1, part 2, *General introduction to fish Acipenseriformes*, pp. 37–37. Wiesbaden, Germany, Aula-Verlag.

Kazancheev, E.N. 1981. *The fishes of Caspian Sea.* Moscow, 166 pp. (Translated by Abolghasem Shariaty, Iranian Fisheries, Tehran)

Keyvanfar, A. & Nasriehari, A. 1997. The result of biometrical and biotechnical studies in Iranian coastal waters of Caspian Sea on independence of *A. percicuse* from *A. gueldenstaedti. J. Applied Ichthyol.*, 15: 1–352.

Khoroshko, P.N. 1972. The amount of water in Volga basin and its effect on reproduction of sturgeons (Acipenseridae) under condition of normal and regulated discharge. *I. Ichthy.*, 12: 608–616.

Kiseleva 1974. *Biological productivity of the Caspian Sea.* Moscow, Nauka.

Kohneshari, M. & Azari, T.G. 1974. *Rearing and reproduction of sturgeon.* Tehran, University of Tehran. 298 pp. (In Persian)

Kokoza, A.A. 1997. Importance of artificial reproduction in preserving Caspian sturgeon. *J. Applied Ichthyol.*, 15: 1–352.

Lagunova, V.S. 1997. Impact of present day conditions on hybridisation abnormal development and reproduction rate of sturgeon in the Volga river. *J. Applied Ichthyol.*, 15: 1–352.

Laloee, F. 1996. Study of sturgeon migration to Tajan and Gorganrud rivers. *Iranian Fisheries Journal*, No.4, Winter: 17–30 .

Lovetsky, A. 1834. Dianosis piscium Acipensernum petinentium, praeprimiseorum qui habitant inaquis Imperii Rossici. Now *Mem. Soc. Natur. Moscou* 3: 253–263. *In* J. Holcik, ed. *Freshwater fishes of Europe*, vol. 1, part 2, p. 161. General introduction to fish. Acipenseriformes. Wiesbaden, Germany, AULA. Verlag.

Lukyanenko, V.I., Popov, A.V. & Terentev, A.A. 1968. Ovidovoi spetsifichnosti syvorotochnykh proteinogramm osetrovykh. *In* J. Holcik, ed. *Freshwater fishes of Europe*, Vol.1, part 2, *General introduction to fish Acipenseriformes*, pp. 294–344. Wiesbaden, Germany, Aula-Verlag.

Lukyanenko, V.I., Karataeva, B.B., Altufev, Yu.V. & Umerov, Zh, B. 1972. Populyassionnaya struktura osetrovykh v svyazi a problemoi ikh zavodskogo vosproizvodstva. *In Biologicheskie resursy kaspiiskogo moray*, pp.105–106. Astrkhan, Izd. Volga,

Lukyanenko, V.I., Vasilev A.S. & Lukyanenko,V.V. 1997. Khabarov population of sturgeon fish. *J. Applied Ichthyol.*, 15: 1–352. **Marti, Y.Y.** 1940. Classification and biology of Russian sturgeon of the Caucasian coast of Black *Sea. Zool. Zhurn* 19(6): 865–872.

Marti, Y.Y. 1979. Development of Sturgeon management in the South Sea of the USSR. *In The biological resources of inland waters of the USSR*, pp. 73–85. Moscow, Nauka.

Moghim, M. & Ganinejad, D. 1994. *Investigation statistic and biologic*. Tehran. 123 pp. (In Persian)

Moghim, M., Ganinejad, D., Hoseinnia, M., Fazly, A. & Amirkany, I. 1996. *Investigation statistic and biologic of capture fisheries of sturgeon in Iran*. Tehran, Iranian Fisheries Research Organization. 107 pp. (In Persian)

Nasrichari, A. 1993. *Study of morphobiology between Russian sturgeon and Persian sturgeon*. Tehran, University of Tehran. (In Persian) (M.Sc. thesis).

Nikolskii, G.P. 1971. *Chastanya ikhtiologia*. Moskow, Izd.Vysshya shkola.

Norouz Fashkhami, M., Pourkazemi, M. & Baradaran Noveiry, S. 1998. *Study of chromosome in A. Persicus from white globule*. First National Symposium on Sturgeon, Rasht, 15–16 December. (In Persian)

Ovenden, J.R. 1990. Mitochondrial DNA and marine stock assessment: a review. *Aust. J. Mar. Freshwat. Res.*, 41: 35–53.

Pashkin, L.M. & Paletiva, V. 1992. *Role of spawning ground of Aktoba River on sturgeon*. Translated to Persian by Uones Adely. Fishery research centre (Bandar Anzali), Gilan province in Iran.

Pavlov, P.I. 1967. Morfologicheskii osobennosti dunaiskoi belugi *Huso hoso* ponticus Sal'nikov et Maliatskii. *Gidrobiologicheskii zhurnal*, 3: 39–42. *In* J. Holcik, ed. *Freshwater fishes of Europe*, Vol.1, part 2, *General introduction to fish Acipenseriformes*. Wiesbaden, Germany, Aula-Verlag.

Podushka, S.B & Levin, A.V. 1993. *Effectiveness of sturgeon restockingin the volga-Caspian Sea region*. International Symposium on sturgeon, 6–11 September. Moscow, Kostroma.

Podushka, S.B. 1997. New method of obtaining eggs in sturgeons. *J. Applied Ichthyol.*, 15: 1–352.

Pourasady, M. 1995. *Report of training sturgeon hatchery in Russia*. Technical report, Rasht, Iran, Shahid Beheshti hatchery. (In Persian)

Pourasady, M. 1996. *Construction of new incubator (osetr) and comparison with Yuschenko incubator*. Technical report, Rasht, Iran, Shahid Beheshti hatchery. (In Persian)

Pourkazemi, M. 1996. *Molecular and biochemical genetic analysis of sturgeon stocks from the South Caspian Sea*. University of Wales. 260 pp. (Ph.D. thesis)

Pourkazemi and Hosseini. 1997. *Iranian report for 10th meeting of CITES*, Harare, Zimbabwe, 9–20 June 1997

Pourkazemi, M. Bahmani, M., Parvaneh, A. & Vahabi,Y. 1997. *Physiological condition of A.stellatus in south of Caspian Sea*. First National Symposium on Sturgeon, Rasht, 15–16 December. (In Persian)

Pour-Qadiri, A.H. 1996. 500kg sturgeons caught. *Ettlaat International*, 10.

Razavni, S.B. 1998. *Ecology of the Caspian Sea*. Tehran, Iranian Fishery Research Organisation. 90 pp.

Rezvani Gilkolaei, S. 1997. *Molecular population genetic studies of sturgeon species in the south Caspian Sea*. (Ph.D. thesis)

Rezvani Gilkolaei, S. 1990. *Sex composition in Caspian Sea and effect the sex reversal in population*. Sustainable exploitation in Caspian Sea. 9–11 October. (In Persian)

Rostami, I. 1961. *Biologie exploitation des sturgeons (Asipenseridae) Caspian's Narle.* Meuse, Duc.

Shafizadeh, S.S & Vahabi,Y. 1996. *Use of LH-RH in reproduction of sturgeon in Shahid Bheshti hatchery in Iran.* Rasht, Iran, Shahid Beheshti hatchery. (In Persian)

Shelukhin, G.K., Altufiev, Yu.V., Romanove, A.A. & Rizvanova, A.V. 1997. Specific features of Caspian sturgeon response to environmental anthropogenic pollution. *J. Applied Ichthyol.*, 15: 1–352.

Sokolov, L.I & Vasiliev, V.P. 1989. *Acipenser nudiventris* Lovetsky. *In* J. Holcik, ed. *Freshwater fishes of Europe*, vol. 1, part 2, p. 161. *General introduction to fish. Acipenseriformes.* Wiesbaden, Germany, AULA Verlag.

Taghavi Motlagh, A. 1996. *Population dynamics of sturgeon in the Southern part of the Caspian Sea.* University of Wales. 300 pp.

Umerov, Zh.G. & Altufev Yu.V. 1968. Sravnitel'nyl analiza vnutrividovoi antigennoi different sivovki osetrvykh kospilskogo. *In* J. Holcik, ed. *Freshwater fishes of Europe*, Vol. 1, part 2, *General introduction to fish Acipenseriformes.* Wiesbaden, Germany, Aula-Verlag.

Vlasenko, A.D. 1994. *Sturgeon status in the Caspian Sea.* International Conference on Sturgeon Biodiversity and Conservation, New York, 28–30 July.

APPENDIX 1

STURGEON REPRODUCTION IN IRANIAN HATCHERIES IN 1996

	A. persicus	*A. stellatus*	*H. huso*
Broodstock capture (numbers)	644.0	236	17
Injected broodstock (numbers)	381.0	165	10
Spawning rate (%)	86.1	54	83.3
Total fecundity (numbers)	256 946.0	138 091	240 458.0
Relative fecundity (numbers)	7 882.7	9 574	2 766.0
Fertilization rate (%)	67.6	44.4	45
Survival rate in incubator (%)	63.1	32.1	38.7
Survival rate in tank (%)	72.1	72.6	74.7
Stocking density (numbers/ha)	82 860.0	99 833	72 941
Survival rate in pond (%)	58.2	54	55.6
Fingerling production (numbers)	10 779 938	316 214	346 300

(Abdolhay and Baradaran Tahori, 1998)

APPENDIX 2

GENETIC RESOURCES OF CASPIAN STURGEON

Species, subspecies and stocks

There are five species of sturgeon belonging to the genera of *Acipenser* and *Huso* in the Caspian Sea. Significant variations both within and between geographical regions were observed in different sturgeon species (Holcik, 1989).

Beluga sturgeon (Huso huso)

There are a number of forms of beluga sturgeon. A series of morphological differences have been observed between the Danube and the Caspian Sea beluga sturgeon (Pavlov, 1967). The type of beluga sturgeon that was considered by Berg (1948) was *Huso huso* and was typical of the Caspian-Volga populations. However, based on antigenic studies of the blood serum protein, three subpopulations of beluga sturgeon from the Volga, Ural and Kura rivers in the Caspian Sea region have also been identified (Karataeva, Lukyanenko and Terentev, 1971). The largest of these is the beluga, which reaches a length of up to 425 cm and weight of 520 kg. For example, Pour-Qadiri (1996) reported that a 414-cm, 500-kg beluga sturgeon was caught on the east coast of the south Caspian Sea. It yielded 54 kg of high-quality caviar. In the past, individuals have reached the age of 100–120 years, but the present life span does not exceed 50–55 years. Sexual maturity is attained at the age of 11 years for males and 16 years for females. For breeding, the beluga sturgeon enters the rivers Volga, Ural, Terek and Sefidroud. They feed on gobies, shads and carp, and during their first month of life in the sea on Mysidaca. At the beginning of the twentieth century (1904–1913) the beluga sturgeon accounted for about 40 percent of the sturgeon catch. At present it accounts for no more than 10 percent (annual report of Shilat in Iran).

Stellate and sterlet sturgeon **(Acipenser stellatus and A. ruthenus)**

There are two forms of stellate surgeon in the Volga basin, the typically resident sterlet (*A. ruthenus*) whose living area is limited to the upper and middle parts of the Volga River, and the semi-migratory stellate that enters the brackish parts of the Caspian to feed. Borozenko (1942) reported two different ecological forms of stellate surgeon in the Caspian Sea, northern and southern forms. The northern form (*A. stellatus stellatus*) has growth rate and fecundity lower than that of the southern form (*A. stellatus cyrensis*).

Immunological studies (Lukyanenko *et al.*, 1972) show that the northern and southern Caspian Sea stellate sturgeon are genetically distinct from each other and have distinct spawning periods in the spring and winter (Nikolskii, 1971).

Based on analysis of the average proportion of the head and the dorsal and anal fins, a subspecies *A. stellatus donensis* from the Azov Sea was reported by Lovetsky (1834) and reconfirmed by Chugunova (1964). However, their suggestion was rejected by Holcik (1989), who argued that those characters are not reliable as they undergo a considerable change during growth and depend upon feeding conditions.

Stellate sturgeon are smaller than beluga and other sturgeons, reaching 195 cm in length and a weight of up to 25 kg, and they also have shorter life spans of 28–30 years. Sexual maturity is reached at 6–8 years. Most of the males attain full growth after 9 years and females after 11 years. Fingerlings in the river and the sea feed on crustaceans. The proportion of stellates in Iranian sturgeon catches has gradually decreased in recent years from 45 percent to 35 percent (Moghim *et al.*, 1996).

Persian sturgeon **(Acipenser persicus)**

The Persian sturgeon (*A. persicus*) prefers warmer water than the beluga and Russian sturgeon. It forages mostly in the Middle and South Caspian Sea and also the Black Sea (Artyukhin and Zarkhua, 1986). It was considered a subspecies of Russian sturgeon (*A. gueldenstaedti persicus*) because of its morphological similarity with the Russian sturgeon. (Berg, 1933). Based on external morphological differentiation, two forms of Persian sturgeon subspecies were recognized as *A. persicus* in the Caspian Sea Basin and *A. persicus colchicus* in the Eastern Black Sea (Marti, 1940). Haematological and biochemical studies during 1984–1988 in coastal waters in Iran and isoelectric focusing clearly identified a significant difference between the Persian and Russian sturgeon (Keyvanfar and Nasrichari, 1997). A partial sequence of the mtDNA ND 5 region gene from five individuals of Persian sturgeon collected from west and east regions from the South Caspian Sea revealed a very low level of divergence. Four of these sequences were identical. The genetic distance between the two different sequences was only 1 percent. Several explanations can be put forward to explain the low levels of sequence divergence observed (Rezvani, 1997). Ovenden (1990) pointed out that it is possible that marine organisms, in general, have a slower rate of mtDNA evolution. However, other factors such as the bottleneck effect can create the low nucleotide divergence (Rezvani, 1997). Spawning grounds are predominantly in the rivers Kura and Volga rather than the Ural. Two races of Persian surgeon spawning at different times in the Sefidroud (Iranian side) were reported by Rostami (1961). The first group spawns at the end of April and in May and the second group spawns during September and October. This sturgeon belongs to the category of fish with mixed feeding habits (eating other fish and bottom invertebrates). Fingerlings in the rivers and after entering the sea feed on mysids and other crustaceans.

The maximum recorded age of Persian sturgeon in the Kura River is 48 years. An individual taken in the Volga was 38 years old. The maximum size reached by Persian sturgeon in the Caspian Sea region was 231–242 cm but at present individuals do not exceed 205–230 cm (Holcik, 1989, Razavi, 1998). The average length for males is 139 cm and for females 155 cm and the average weight is 20.1 kg and 29.9 kg, respectively (Moghim and Ganinejad, 1994). Persian sturgeon reaches sexual maturity later than Russian sturgeon. In the Kura River the males mature at age 8 years and the females at 12 years. In the Volga and Ural rivers maturity is reached at the age of 15 years for males and 18 years for the females (Holcik, 1989).

Russian sturgeon (Acipenser gueldenstaedti)

The Russian sturgeon lives in the Caspian Sea, Volga and Kura rivers, Black Sea (Rioni Dnieper Rivers) and the Azov Sea (Don River). The forms in these rivers are well differentiated from each other. Different stocks of Russian sturgeon from the Volga and Kura rivers have been identified (Belyaeva, 1932, 1972; Kazancheev, 1981). Immunological analysis of all these stocks has revealed a high degree of differences between fish from different geographical regions (Umerov and Altufev, 1968; Lukyanenko, Popov and Terentev, 1968).

Several races of summer and winter migratory forms of Russian sturgeon were also reported in the Volga River (Barannikova, 1991). Marti (1940) classified two varieties of Russian sturgeon inhabiting the Black Sea as *A. gueldenstaedti* var. *tanaica* and *A. gueldenstaedti* var. *colchicus*. However, Berg (1948) called the latter a subspecies *A. guedenstaedti colchicus* (Marti). By contrast, because of a great similarity of this subspecies to Persian sturgeon, Artyukhin and Zarkua (1986) called it *A. persicus colchicus*. Russian sturgeon is representative of sturgeon species that are commercially exploited throughout the Caspian Sea. Identification of its genetic variability and stock structure will provide useful information for conservation and fishery management. Sixty-two fish samples representing two different populations from the South Caspian Sea (west and east areas) were investigated using PCR amplification of the mtDNA ND 5/6 gene regions. PCR fragments of all individuals (2400 bp) were digested with ten restriction enzymes (Rezvani, 1997). Significant differences in the distribution of haplotype frequencies were observed between populations. The average nucleotide and haplotype diversity over all populations were 0.029 and 0.95, respectively. The value of nucleotide divergence between west and east populations was only 0.052 percent but a χ^2 test based on haplotypes showed significant differentiation between the two (Rezvani, 1997). This result was in contrast with that obtained in a study based on the mtDNA 100-bp region of Russian sturgeon from the South Caspian Sea, where no significant differentiation among populations from four wide regions was observed by Pourkazemi in 1996 (Rezvani, 1997). Overall, these data suggest that the Russian sturgeon populations in the South Caspian Sea comprise at least two stocks.

Russian sturgeons enter the rivers Volga, Ural and Terek for reproduction. The largest stocks occur in the Volga, up to the Volgagrad dam. Fish reach 200–210 cm in length with a weight of 60–65 kg, and can live up to 40 years. Males reach sexual maturity at the age of 7 years and females at 8 years. Maximum size for most males occurs at 14–17 years, and for females at 18–21 years. Russian sturgeon are found in coastal shallows at depths from 2 to 100–130 m with large numbers at depths of less than 50 m.

Ship sturgeon (Acipenser nudiventris)

Kazancheev (1981) identified two reproductively isolated groups known as the North and South Caspian ship sturgeon populations. These populations differ slightly from the typical form from the Ural Sea. At the present time, because of the drying of the Ural Sea, *A. nudiventris* as well as other species have become extinct in the wild there.

The ship sturgeon is a large fish; at maturity individuals grow to over 200 cm and 75 kg. For breeding it enters the rivers Kura, Ural and Sefidroud, but it is rarely found in the Volga. Most of the males mature at the age of 9–13 years, and females at 13–16 years. It forages mainly in the middle and South Caspian Sea, along the western shores at depths of 11–25 m, and feeds on fish and bottom invertebrates. Fishing for the ship sturgeon is now prohibited in the Ural River because of depletion of stocks. The ship sturgeon is of relatively minor significance for Caspian catches.

Karyotype

Studies of sturgeon karyotype provide information about both the evolution and the polyploidization event in this group on ancient fish. The karyotype of the sturgeon is among the most complicated of the vertebrates and has not yet been studied in sufficient depth. In most sturgeon species a large number of chromosomes are present, about half of which are microchromosomes (Vasiliev, 1980, and references cited in Birstein and Vasiliev, 1987). Sturgeon can be divided into two groups based on the number of chromosomes.

First group: species carrying 120 chromosomes or tetraploid (e.g. *Huso huso*, *H. dauricus*, *A. ruthenus*, *A. stellatus*, *A. nudiventeris*). Second group: sturgeon with 240 chromosomes or octoploid (e.g. *A. naccarii*, *A. gueldenstaedti*, *A. baeri*, *A. persicus*).

The chromosome numbers of five sturgeon species of the Caspian Sea are given in Table 14. Study of sturgeon genome size using flow cytometry methods has revealed that there is a correlation between the number of chromosomes and genome size (DNA content per nucleus). In *H. huso* (2n = 120), the DNA content reaches 3.6 pg per nucleus, whereas in *A. naccarii* (2n = 240) DNA content = 5.7–6.3 pg per nucleus (Fontana, 1976). Birstein (1993) studied the DNA content in ten Eurasian sturgeon species using flow cytometry methods. They concluded that the average DNA content in tetraploid sturgeon ranges from 3.17 to 4.04 pg and in octoploid sturgeon species (*A. gueldenstaedti*) from 3.17 to 8.31 pg. The DNA content in Sakhalin sturgeon (*A. medirostris* = *A. mikadoi*) is estimated to be twice as high as in the octoploids, 13.93–14.73 pg, and they concluded that the ploidy level of Sakhalin sturgeon may be 16n and number of chromosomes could be 500 (Birstein, 1993).

TABLE 14. Chromosome numbers of sturgeon in the Caspian Sea

No.	Species	Chromosome no. (2n)	References
1	*Huso huso*	118 ± 2	Birstein and Vasiliev (1987)
2	*A. stellatus*	118 ± 2	Birstein and Vasiliev (1987)
3	*A. nudiventeris*	118 ± 2	Sokolov and Vasiliev (1989)
4	*A. gueldenstaedti*	250 ± 8	Birstein and Vasiliev (1987)
5	*A. persicus*	250 ± 10	Norouz Fashkhami, Poukazemi and Baradan Noveiry (1998)

Flounder stock enhancement in Miyako Bay, Japan

Hiroyuki Okouchi
National Center for Stock Enhancement (formerly the Japan Sea-Farming Association)
Miyako Station, 4-9-1 Sakiyama, Miyako, Iwate, 027-0097 Japan

Shuichi Kitada
Tokyo University of Marine Science and Technology (formerly Tokyo University of Fisheries), 4-5-7 Konan, Minato, Tokyo, 108-8477 Japan

Akio Iwamoto
National Center for Stock Enhancement (formerly the Japan Sea-Farming Association)
Yashima Station, 2-3-4 Yashima-higashimachi, Takamatsu, 761-0011 Japan

Tatsuhiro Fukunaga
Japan Sea-Farming Association (after 1 October 2003, Fisheries Research Agency – Stock Enhancement Division), Queen's Tower B 15F, Minatomirai, Nishi-ku, Yokohama-shi, Kanagawa 220-6115 Japan

ABSTRACT

This paper reviews the flounder stock enhancement programme around Miyako Bay, Japan, during the period from 1980 to 1995 focusing on the stocking effectiveness of the nine releases from 1987 to 1995 evaluated by the fish census at Miyako Fish Market. We analysed the data of all landed flounder for 132 months from June 1988 to May 1999. A total of 368 986 flounder were landed, of which 106 331 (28.8%) were hatchery-produced and 262 655 (71.2%) were naturally produced fish. Return rates ranged from 5.9 percent to 23.3 percent, with average of 12.2 percent. Estimates of economic efficiencies were between 0.46 and 2.53, and seven releases exceeded the break-even point of 1.0. Flounder release was found to be economically feasible when sound juveniles were released in August and early September. Release of large-sized juveniles proved advantageous for high return rates. The most efficient size at release was detected at total length (TL) of 90 mm. The stock enhancement programme was considered to augment fishery production without displacement of natural fish. The stocking programme raised awareness among the fishers of the need to conserve small fish, which enabled a regulation to be implemented that prohibited catching flounder of body length under TL 30 cm. The yield per release ranged from 15.7 to 75.5 g before this regulation was begun, and was raised to 89.8 g in 1995 after its implementation, showing that the regulation worked effectively both for hatchery and natural flounders and improved the yield per release/recruit. General lessons, strengths and weaknesses, future prospects and limitations to the programme are discussed.

INTRODUCTION

The stock enhancement programme of marine resources in Japan, supported by the Japanese Government, began in 1963 by targeting important commercial coastal fishery resources. The programme has been reviewed, focusing on its organization (Imamura, 1999) and stocking effectiveness (Kitada, 1999). Flounder is one of the main target species of the programme. The number of annually released juvenile flounder exceeded one million in 1980 and 30 million fish were released from 37 of 39 prefectures facing Japan's coastal waters (Anon., 2000a).

It is necessary to survey a wide area to estimate stocking effectiveness of finfish species such as flounder, which migrate widely and which are landed at many fish markets. A method for estimating stocking effectiveness based on two-stage sampling designs has thus been developed, and related parameters were first estimated with precision in a case study of flounder (Kitada, Taga and Kishino, 1992). Estimates of stocking effectiveness have also been reported for abalone (Kojima, 1995) and masu salmon (Miyakoshi *et al.*, 2001) using the same method. However, there have been few case studies evaluating the stocking effectiveness with appropriate procedures, although this measure has been one of the most important issues in Japan's stock enhancement programmes.

Miyako Station of the Japan Sea Farming Association (JASFA) has been involved in developing juvenile production technologies for flounder and has been involved in evaluating stocking effectiveness around Miyako Bay since 1984 for the Fisheries Agency of Japan. Miyako Bay was considered to contain nursery grounds of juvenile flounder and was therefore a suitable release site. Released flounder are caught in an area 30 km north and 20 km south of the mouth of the bay, almost all being landed at Miyako Fish Market (MFM). We have therefore carried out a census of landed flounders at MFM since 1988 to give a precise estimate of stocking effectiveness rather than by introducing sample surveys. Released flounders landed have been distinguished from naturally produced fish by the characteristic pigmentation on the abocular side of hatchery-produced flounders. In addition, the brand marking and alizarin complexone (ALC) otolith marking have been used to determine the age composition of recaptured flounder.

The objective of this paper is to review the results of the flounder stock enhancement programme in Miyako Bay during the period from 1981 to 1998 and to discuss their implications for the programme. We analysed the nine releases from 1987 to 1995 and estimated the stocking effectiveness with an index of the economic efficiency based on the census data. Relationships between return rates and stocking variables such as size at release, release timing and quality of juveniles were examined. Effects of the body length regulation on the stocking effectiveness and the interaction between hatchery- and naturally produced stocks are discussed. Finally, we discuss general lessons and the strengths and weaknesses of the programme.

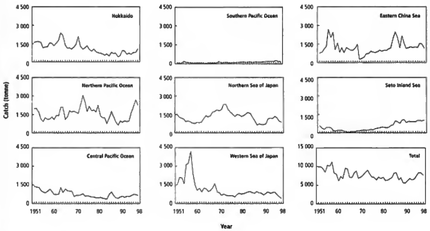
REVIEW OF FISHERY

Status of flounder catches in Japan

Flounder is one of the main target species of Japan's stock enhancement programme and is also important for coastal fisheries as well as for aquaculture. Based on the annual statistical report of fisheries and aquaculture production, the catch of Japan's coastal fish species in 1998 excluding pelagic fish was 1 161 374 tonnes (of a total catch of 5 314 826 tonnes), of which 0.66 percent was flounder (7 615 tonnes). Fishery production for the coastal area in 1998 amounted to 309 589 million yen; total production amounted to 1 337 903 million yen. Of the total coastal fish production, 5.19 percent (16 068 million yen) was from flounder. Aquaculture production of marine fish totalled 258 801 million yen, of which 5.88 percent (15 219 million yen) came from flounder production (Anon., 2000b).

The average total catch of flounder in Japan from 1951 to 1998 was 7 707 tonnes, with maximum a of 11 198 tonnes in 1957 and a minimum of 5 517 tonnes in 1990. Catches in Hokkaido, the northern Pacific Ocean and the central Pacific Ocean had decreased annually until the mid 1980s but there has been an upward trend since then. The Eastern China Sea, the Seto Inland Sea and the southern Pacific Ocean show the same upward trend from around the 1970s. By contrast, in both fishing areas in the Sea of Japan, catches of flounder have decreased and remained at low levels. Among all these areas, the northern Pacific Ocean has shown a remarkable increase, and this area includes Iwate Prefecture (Figure 1).

FIGURE 1. Changes in annual catch of flounder at the eight study-areas in Japan

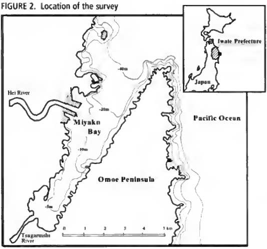


Status of flounder catches in Iwate Prefecture and Miyako Bay

Iwate Prefecture is located on the northern Pacific Ocean side of Honshu, the main island of Japan, and Miyako Bay is located mid way along the Iwate Prefecture coastline (Figure 2). The average catch of flounder in Iwate Prefecture from 1951 to 1998 was 89.9 tonnes, with a maximum of 158 tonnes in 1963 and a minimum of 30 tonnes in 1989. The trend in caught flounder showed a steep drop in 1989 but has began to increase and reached historical highest level of 155 and 156 tonnes in 1997 and 1988 (Figure 3).

Catch statistics are also available for MFM from 1956, which is the principal fish market in the area around Miyako Bay, and about 90 percent of the flounder catch in the area can be determined from the catch statistics of MFM. The average catch of flounder from 1956 to 1998 was 17.1 tonnes. The maximum catch was 38 tonnes in 1963 and minimum 5 tonnes in 1982. The flounder catch at MFM was on a decreasing trend from 1980 to 1990, but with large annual fluctuations. In the 1990s, the catch trend was upward and catches have recovered to a level of 20 tonnes in 1997 and 1988 (Figure 3).

FIGURE 2. Location of the survey



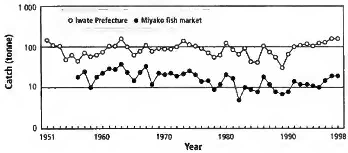
At MFM, landed flounder in 1998 was 19 tonnes (0.05 percent of the total landings) and 40 million yen (0.5 percent of the total catch value). The contribution of flounder to the total fishery production was thus small. However, flounder is traded at a high price (Table 1) and is caught by small-scale fishing operations (Figure 4). Flounder is an important resource for these small-scale fishing operations, to which many coastal fishers around Miyako Bay belong.

Unique features of the fishery around Miyako Bay

Setnet, small setnet, gillnet and longline fisheries are all operated off the coast around Miyako Bay. Trawl fisheries operate in the offshore area but small trawlers are not used in the coastal areas. The setnet fishing season lasts for ten months, from May to February, in the central part and mouth of Miyako Bay and along the coast facing the open sea. The small setnet fishing season lasts for six months, from March to August, largely at the central and inner parts of Miyako Bay. Trawlers fish for ten months from September to June, in waters 200 m deep around the central and northern parts of Iwate Prefecture, which includes the offshore area of Miyako Bay.

Fishers in this area mainly belong to one of three cooperative fishery associations, Miyako, Taro or Omoe. The number of regular members of the Miyako, Taro and Omoe cooperative associations is 1 205, 567 and 573, respectively. The gives a total for the three associations of 2 345, or about 3 800 if associate members are also included. The aggregate number of fishery units of the three associations is 18 for setnets, 55 for small setnets, 395 for gillnets and three for trawlers. It is difficult to determine the number of fishery units using longlines because this method is not licensed in the area. However, many fishers are engaged in longline fishing during the summer, when they can obtain live bait such as anchovies.

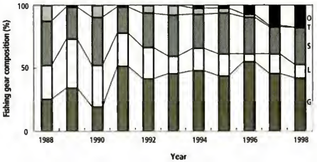
FIGURE 3. Changes in annual catch of flounder for whole Iwate Prefecture and the Miyako fish market



Judging from annual production, setnets seems to be the principal fishing method in this area. Also of importance are gillnets and longlines operated by individuals on a small scale. Many of these small-scale fishers are also engaged in aquaculture businesses harvesting scallops, oysters and seaweed or in fisheries harvesting abalone, sea-urchin and seaweed as an aside.

In the area around Miyako Bay, setnets, small setnets, gillnets and long lines are used to catch flounder (Figure 4). Setnets (including small setnets) and longlines were the dominant fishing methods from 1988 to 1990, and these fishing methods accounted for about 70 percent of the total numbers caught. However, catches by gillnets have increased since 1991 and this now accounts for about 50 percent of the total landings of flounder.

FIGURE 4. Change in fishing gear composition of flounder as a percentage of the number of fish landed at the Miyako fish market



From June 1995 to May 1996, 16 setnets, 16 small setnets, 107 gillnets, 17 long lines and three trawlers landed flounder at MFM; these were all members of the Miyako, Taro and Omoe fisheries cooperative associations. The ratio of fishery units that landed flounder at MFM to the total number of fishery units for each fishing method was 89 percent for setnets, 29 percent for small setnets, 27 percent for gillnets and 100 percent for trawlers. The ratios for small setnets and gillnets were low because the number of fishers actually operating was smaller than those permitted to operate. Most fishers operating in the area around Miyako Bay actually fish for flounder.

Principal problems with fishery around Miyako Bay

MFM is the only principal fish market in the area around Miyako Bay; total landings accounted for 38 319 tonnes and 9 043 million yen in 1998. Data for landings by fish species at MFM in 1998 showed that saury ranked first with 13 375 tonnes, or 34.9 percent of total weight, and salmon (chum salmon comprised 99 percent with the remainder being pink, coho and Chinook salmon) ranked second with 8 089 tonnes, or 21.1 percent of total weight. These two species accounted for 56 percent of the total landings by weight. Data based on value showed that saury ranked first at 3 410 million yen (37.7 percent of the total landings), and salmons ranked second at 3 044 million yen (33.7 percent of the total). These two species accounted for 71.4 percent of the total revenue of landings (Table 1).

TABLE 1. Ranking for landings by weight, value and unit price at the Miyako fish market (1998)

Landings in weight				Value				Unit price		
Rank	**Species**	**Weight (tonnes)**	**%**	**Rank**	**Species**	**Value (×1000 yen)**	**%**	**Rank**	**Species**	**Price (yen/kg)**
1	Saury	13 375	34.9	1	Saury	3 410 625	37.7	1	Sea urchin	6 933
2	Salmon[1]	8 089	21.1	2	Salmon[1]	3 044 438	33.7	2	Bluefin tuna	3 411
3	Pollock	3 727	9.7	3	Cod	544 500	6.0	3	Kichiji rockfish	2 257
4	Cod	3 630	9.5	4	Kichiji rockfish	291 153	3.2	4	Flounder	2 154
5	Octopus	617	1.6	5	Octopus	264 076	2.9	5	Red rockfish	1 982
6	Squid	565	1.5	6	Squid	172 325	1.9	6	Tuna[2]	1 711
7	Mackerels	394	1.0	7	Sea urchin	145 593	1.6	7	Sea cucumber	1 260
8	Soles	213	0.6	8	Soles	145 479	1.6	8	Bigeye tuna	957
9	Sardine	184	0.5	9	Pollock	145 353	1.6	14	Salmon[1]	376
10	Striped marlin	139	0.4	10	Swordfish	103 124	1.1	18	Saury	255
18	Flounder	19	0.05	11	Flounder	40 926	0.5	23	Cod	150
				12	Yellowtail	38 418	0.4			

[1] Chum salmon occupies over 99%. Others are pink, coho and chinook.

[2] Except for bluefin, longfin, bigeye and yellowfin tuna

Saury is the most important fish for offshore fishing industries, and the main fishing area is offshore around Hokkaido. By contrast, landings of chum salmon from local coastal fisheries are substantial around Miyako Bay. Data from the hatchery-release programme show that the number of returned chum salmon increased after around 1975, with total landings reaching 10 000 tonnes in 1984, from a value that had been below 1 000 tonnes before 1974. However, the unit price of chum salmon fell remarkably after 1995, mainly as a result of the over production of local chum salmon and increased importation of salmon. The number of returned chum salmon then began to decrease from 1997, and this has had a serious influence on the fisheries community around Miyako Bay. The fisheries cooperative associations and the fishers need to have various fishery resources in order to stabilise production.

The Fisheries Agency of Japan began the stock enhancement programme of flounder in 1980 with concern over the decrease of flounder catches in northern Japan during the 1970s (Figure 1). Despite a strong demand for scientific evaluation of stocking effectiveness, there have been few case studies completed. The Fisheries Agency therefore entrusted the evaluation of flounder stocking programmes to the JASFA and Miyako Station initiated surveys at MFM in order to obtain precise estimates of stocking effectiveness.

Stock enhancement programmes have two roles: to augment fishery production by releasing hatchery-produced juveniles and to supplement reproduction. There are no natural spawning grounds in Miyako Bay and the source of natural larvae from outside the bay is unknown. The programme was therefore aimed at augmenting fishery production by releasing hatchery-produced juveniles. We set two goals for the programme: to detect suitable release sites and sizes at release, and to evaluate the stocking effectiveness quantitatively.

METHODOLOGY OF STOCK ENHANCEMENT

Broodstock selection and management

JASFA Miyako Station has developed juvenile production technologies since 1980. The broodstocks were a mix of wild fish caught in the area around Miyako Bay (two or three years of age) and progenies produced at Miyako Station (shown in Appendix 1).

The broodstock was reared in two circle-shaped concrete tanks 80 m^3 in volume. Ratios of males to females were adjusted to 0.5. Fertilized eggs obtained by natural spawning in these tanks were used for juvenile production. Natural spawning continued from late April to early June, but we used eggs spawned during early May as this was the high spawning season.

The broodstock used from 1988 to 1995 for juvenile production largely consisted of progenies produced from wild fish initially introduced to Miyako Station. The broodstock remained largely unchanged during in this period. However, these broodstocks were discarded in 1995 because a large number of juveniles died and viral diseases were suspected to have been introduced into the production process. In 1996, we used another broodstock reared from hatchery progeny, and began to collect wild matured flounders landed on MFM to prepare new broodstocks. In 1997, all broodstocks reared from hatchery progeny were disposed of and new broodstocks that comprised only wild fish were established. We carried out a blood test for all individuals of broodstock candidates after 1996. Fish with an antibody level that exceeded a threshold value were judged to be virally infected and were discarded.

Juvenile production

JASFA Miyako Station initiated juvenile production of flounder in 1980. Flounder juveniles are reared in 50 m^3 concrete tanks at a water temperature of 16 or 17 °C. Flounder larvae were fed with rotifers (3–30 days after hatching), *Artemia nauplius* (12–45 days after hatching) and an artificial diet (20 days and thereafter). We finished the larval rearing period when the hatched flounder larvae were up to 30 mm in total length (TL) at 50 days after hatching, and we then evaluated the results. Since 1988, the technology of juvenile production has given stable results regarding fish survival and health. The average survival rate during the larval rearing period from 0 to 50 days after hatching reached 80.9 percent (range, 56.1–88.7 percent). However, it remained difficult to prevent perfectly the appearance of black pigmentation on the abocular side of the fish.

Juveniles of TL 30 mm were moved to net cages set in another concrete tank 120 m^3 in size, and were reared up to the size at release of TL 80 mm in these net cages for 40–50 days. Because cannibalism was observed during this period as a result of the large size difference between individuals, we separated small juveniles of inferior growth from normal-sized juveniles when the average total length reached 35 mm, 45 mm and 60 mm. Juveniles of slow growth were moved to other cages and continued to be reared.

Genetic resource management

It have been a requirement that released fish do not affect the genetic diversity of wild stocks. The first approach with this in mind is to examine the genetic structure of the target species. It has been suggested that the flounder stock of the Sea of Japan can be separated into two groups of north and south based on the difference in the number of dorsal fin rays. By contrast, allele frequencies of mitochondrial DNA (mtDNA) of flounder have suggested a homogeneous population structure along the entire coast of Japan (Tanaka *et al.*, 1997). There were no clear genetic differences among fish from sampling sites along the Pacific coast including Miyako Bay (Asahida *et al.*, 1998).

The research team consisted of individuals from Kitasato University, Tohoku National Fisheries Research Institute and the JASFA, who examined the genetic diversity of hatchery-produced flounder juveniles through mtDNA analysis. Samples of juvenile flounder produced in five prefectural sea-farming centres (hatcheries), the JASFA Miyako Station and wild flounders landed in Ibaraki, Kanagawa, Tokushima, Kagoshima and Yamagata Prefecture were analysed. The results showed that juveniles produced from wild broodstock had similar genetic diversity to the wild stocks. By contrast, juveniles produced from hatchery-produced fish or from mixed broodstocks of wild and hatchery-produced fish had lower genetic diversity (data not shown). The results suggested the importance of using wild fish caught from local sea waters for the broodstocks to maintain the genetic diversity of the wild stocks, as pointed out by Bartley, Kent and Drawbridge (1995) and Harada, Yokota and Iizuka (1998).

Fish health management

A careful health management of broodstocks and juveniles has been continued at the JASFA Miyako Station by maintaining appropriate rearing density of fish, quantity of feed, exchange rate of rearing water and careful observation of fish. Among these operations, the most careful attention was given to disease management. To keep infections to a minimum, we sterilized the rearing tools, tanks and equipment, and the tools and those in charge were exclusive to each rearing tank.

When symptoms of disease were observed, blood samples were taken and examined quickly. If a disease was diagnosed as bacterial, we improved the rearing conditions and used permitted medication. If there was a strong chance of the infection spreading to healthy fish, the diseased fish were disposed of and rearing tanks and equipment were sterilized. If the disease was judged to be viral, we disposed of all fish in the tanks immediately. At the same time, we examined fish reared in other tanks in parallel for virus infection and disposed of the fish if a positive result was obtained. In the JASFA Miyako Station, a bacterial disease occurred in 1984 and a viral disease occurred from 1996 to 1998; we therefore incinerated all juveniles produced in each of these years.

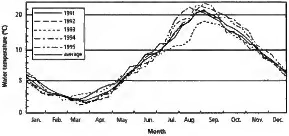
Release site selection

Flounder release experiments and follow-up surveys in the area around Miyako Bay have been carried out since 1980. At the early phase of the survey before 1984, juveniles with external tags were released at Miyako Bay and around Taro Bay and the Sakiyama coast (Appendix 2). Movement patterns of released fish were surveyed based on tag recoveries reported by fishers. The result showed that flounders released in Miyako Bay moved within a narrower range than the fish released at the other two sites. Miyako Bay was considered to have specific conditions that made flounder juveniles more likely to settle down.

Miyako Bay is a narrow bay 4 km wide at its mouth and extending inland for 10 km (Figure 2). The depth at the mouth is 40 m, which is the deepest part of the bay and it gradually becomes shallower as it extends inland. Two rivers flow into the bay: the Hei River into the central western part and the Tsugaruishi River into the inland part. The surface water temperature near the centre of the bay fluctuates within a range 6–22 °C. Lowest temperatures are observed in mid or late March when snowmelt flows in and highest temperatures in late August or early September (Figure 5). Tidal flats expand in to the inner part of Miyako Bay, which is strongly affected by river water. Mysid and goby juveniles are particularly dense there and they form the principal bait for flounder juveniles (Yamada *et al.*, 1994, 1998). These results showed that the inner part of Miyako Bay was a suitable location as a nursery for flounder juveniles, and the release sites have been fixed in Miyako Bay since 1986.

Release strategy

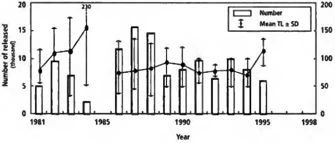
FIGURE 5. Seasonal changes in surface water temperature in Miyako Bay



All or part of the released juveniles were marked except those released in 1980 and 1981. The total number of flounder juveniles released around Miyako Bay was 1 205 000 for the 16 years from 1980 to 1995, of which 1 038 000 fish were released actually in the Bay. The actual number each year ranged from 22 000 to 157 000 and the average TL at release ranged from 70 mm to 157 mm (Figure 6, Appendix 2).

Before 1988, the technology of juvenile flounder production was unstable and the numbers of released fish fluctuated widely. Since 1989, however, 60 000–100 000 juveniles have been released consistently every year. The size at release varies with the time at release and the type of tags or markers used, but the standard size has been kept at TL 80 mm since 1986. In addition, 245 000 small juveniles with an average TL of 25 mm were released in 1980 for a pre-survey, and 633 000 small juveniles with an average TL of 21.0–32.0 mm were released in 1989 and 1990 to examine the feasibility for releasing small-sized juveniles. No release was carried out in 1985 because production ended in failure as a result of a bacterial disease outbreak. The juvenile release experiments after 1982 can be divided into three periods, namely Phase I (1982– 1984), Phase II (1986–1988) and Phase III (1989–1995) according to the objectives of the releases (Appendix 2).

FIGURE 6. Changes in annual number of released flounder and average size at release of juvenile flounder at Miyako Bay



Phase I (1982–1984)

The objective of the survey in this period was to understand movement and dispersal patterns of released flounders and to detect suitable release sites. External tags such as anchor and disk tags were mainly used in order to obtain recapture reports from fishermen. Juveniles were reared to the size at release of TL 100 mm or larger because anchor and disk tags heavily burdened small fish. As the rearing period was extended to include larger juveniles, the time at release occurred later in October or early November. Different coloured and shaped tags were attached to each group to identify fish groups released at different sites and years.

Phase II (1986–1988)

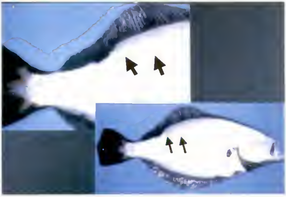
The objective of the survey was to estimate stocking effectiveness. The survey procedure was changed from recapture reporting to sample surveys at MFM. The survey of landings at MFM started in 1986 and was initially conducted only for the high fishing season of flounder between June and August. An inspector was stationed at the fish market in 1988 and all flounder landed were checked on about 280 days in the year when the market was open.

Using non-shedding marks was important rather than using visible external tags because the inspectors examined marked fish in the catches at the fish market, and mark–recapture reports from fishers were not expected. We therefore used as a natural mark the black pigmentation that appears on the abocular side in almost 100 percent of hatchery-released fish. However, it was not possible to distinguish the year of releases using this pigmentation. Ratex marking was then used to identify the year of release and the release groups with different sizes at release within the same year. Rubber-like ratex of different colours was injected hypodermically to the abocular side of the juveniles, which could be easily detected externally. However, the use of ratex marking was abandoned in 1988 because a food hygiene problem was discovered. All releases were completed in September or in early October before the water temperature dropped.

Phase III (1989–1995)

In this phase, we carried out an extensive fish census to evaluate stocking effectiveness precisely. We continuously used the pigmentation as a natural mark and marked 100 percent of released juveniles by using brand and ALC marking. Brand marking was carried out on dorsal and caudal fins on alternate years to distinguish the year of release. Brand marks refer to scars made by penetrating the basal part of the dorsal fin or anal fin of a flounder juvenile from the abocular side with a heated soldering iron, which could then be observed as a round and transparent mark on the abocular side of landed released flounder (Figure 7). Brand marking could be used on juveniles larger than TL 70 mm, so the size at release was fixed at TL 80–90 mm.

FIGURE 7. Released flounder landed at Miyako fish market. The age was identified by the brand marks (arrows; TL 32.0 cm, age 2+)



ALC otolith marking (Kuwada and Tsukamoto, 1987) was simultaneously introduced to distinguish between groups released in the same year with different sizes at release so as to compare the effect of the size on stocking effectiveness. ALC marks could be observed as a fluorescent circle on the otolith of landed hatchery-reared fish. We used a single circle marked at TL 30 mm and double circles marked at TL 30 mm and 50 mm to distinguish the release groups. ALC otolith markings were also used to examine the feasibility of releasing juveniles smaller than TL 20–30 mm.

We attempted to bring forward the time at release and completed the release in early August at the earliest and in mid September at the latest. From 1996 to 1998, no release of flounder juveniles was conducted in Miyako Bay because of the viral disease problem in juvenile production detailed earlier.

MONITORING AND EVALUATION PROGRAMME

Fish census at the market

As mentioned above, all flounder in the landings have been checked on all landing days at MFM since 1988, and we have termed this the fish market census. Most of the flounder landed at the market are stocked alive in small tanks. The inspector was allowed to examine live fish. The following four items were recorded at the fish market for every flounder: (1) pigmentation on the abocular side, (2) total length, (3) external marking and (4) fishing method.

Flounder with pigmentation were judged as released and those without pigmentation as natural. For fish with ratex or brand marks, we recorded the type of marks, the colour and body length measurements, which allowed us to determine the year of release. Because the labels attached on the tanks in which landed flounders were stocked gave the name of the fishers and the fishing vessels, we were also able to identify the fishing method for individual flounder.

Age determination of landed flounder

The census of all the flounder landed at MFM enabled us to distinguish whole landings of released and natural flounder caught around Miyako Bay. However, in order to estimate return rates, we had to estimate the age composition of released flounders landed. The spawning period of flounder in the coastal waters of the northern Pacific Ocean around Japan was estimated to occur in June or July and larvae of natural flounder settled in the shallow water were observed after late June in Miyako Bay. We therefore assumed that 1 June was the date of birth and the period from June to May of the following year referred to the same cohort.

Because 100 percent of the flounder juveniles released from 1989 to 1995 were marked by brand and ALC marking (Appendix 2), the age of recaptured flounder could be determined. As very many flounder with marks were recaptured, we were able to estimate the mean TL and standard deviation (SD) by month with high accuracy. We converted length frequencies to age compositions of released flounders with brand marks. We estimated age compositions of released fish with no brand marks or marks that had disappeared by using TLs and SDs of brand-marked fish landed (Okouchi, Kitada and Iwamoto, 1998; Appendix 3). No difference in the growth of brand-marked and unmarked flounders was confirmed in the rearing experiment for 13 months after marking. Landed flounders were divided into three cohorts of age 1+, age 2+ and age 3+. Most of flounders landed at MFM were age 1+ and 2+, and thus we treated the remaining fish as age 3+ because age 0+ fish were never caught around Miyako Bay. Most flounders for the cohort of age 3+ were actually age 3+ and older fish were rare.

Measures of success

We estimated the number of landings of flounder for hatchery- and naturally produced fish by age classes for the nine releases from 1987 to 1995. Contribution rates of released fish to the annual fishery production were calculated for number, weight and the monetary value. Return rates were determined by dividing the number of landings of released fish by the total number of released fish. Economic efficiency were evaluated as the ratio of the total value of landings of released fish to the release costs.

TABLE 2. Results of the flounder census (weight, kg; value, 1000 yen) at the Miyako fish market from 1988 to 1998

Survey year	Landings	Total	Hatchery-released fish			Natural fish	Total	Contribution of hatchery fish (%)
			1+	2+	3+			
1988	Number	4 394	3448	905	41	21 659	26 053	16.9
	Weight	810	533	245	32	9087	9897	8.2
	Value	887	475	285	126	22 613	23 500	3.8
1989	Number	8 926	2751	5143	1032	8020	16 946	52.7
	Weight	2 059	385	1288	386	3568	5627	36.6
	Value	2 621	331	1553	737	8782	11 403	23.0
1990	Number	15 311	9004	5605	702	38 109	53 420	28.7
	Weight	4 642	1976	2023	643	11 122	15 759	29.5
	Value	7 591	1890	3393	2313	18 257	25 849	29.4
1991	Number	14 923	7214	5994	1715	21 854	36 777	40.6
	Weight	5 078	1511	2349	1218	9646	14 727	34.5
	Value	9 185	1434	4273	3478	21 585	30 770	29.9
1992	Number	19 415	13 495	4808	1112	20 626	40 041	48.5
	Weight	6 366	3456	2027	882	10 359	16 725	38.1
	Value	10 218	3328	4052	2841	27 163	37 381	27.3
1993	Number	12 437	5064	6645	728	23 396	35 833	34.7
	Weight	4 705	1176	2864	665	10 265	14 970	31.4
	Value	8 672	1070	5366	2236	21 966	30 638	28.3
1994	Number	10 051	5982	3426	643	20 474	30 525	32.9
	Weight	3 682	1576	1417	689	10 270	13 952	26.4
	Value	6 936	1666	2656	2613	24 630	31 566	22.0
1995	Number	4 699	2052	2403	244	23 844	28 543	16.5
	Weight	2 498	832	1361	305	13 423	15 921	15.7
	Value	6 179	1230	3517	1 432	33 210	39 389	15.7
1996	Number	3 718	530	2445	743	21 162	24 880	14.9
	Weight	2 468	204	1292	972	13 347	15 815	15.6
	Value	6 844	285	2878	3681	35 386	42 230	16.2
1997	Number	10 678	0	8365	2313	37 501	48 179	22.2
	Weight	5 840	0	3969	1871	22 662	28 502	20.5
	Value	14 703	0	8693	6010	63 077	77 780	18.9
1998	Number	1 779	58	461	1260	26 010	27 789	6.4
	Weight	1 487	18	254	1215	16 106	17 593	8.5
	Value	5 316	16	682	4618	51 302	56 618	9.4
Total	Number	106 331	49 598	46 200	10 533	262 655	368 986	28.8
	Weight	39 634	11 668	19 088	8877	129 856	169 488	23.4
	Value	79 152	11 726	37 348	30 085	327 971	407 124	19.4

Based on the length measurement data, we estimated the individual weight by length class based on the length–weight relationship of natural flounder in the Northern Pacific coast of Japan including Miyako Bay ($W = 0.000003117 \times L^{3.125}$; Kitagawa *et al.*, 1994). We then estimated the weight of landings of both released and natural flounder by month and age by multiplying the number of individuals for each length class by the estimated individual body weight of the length class obtained from above length–weight relationship. Total value of landings were estimated by using the unit price of flounders derived from the statistics of the fish market.

The release costs per flounder juvenile was estimated at 3.9 yen for TL 15 mm, 8.2 yen for 30 mm, 33.5 yen for 50 mm and 74.5 yen for 100 mm based on the data from 1985 to 1987 at the JASFA Miyako Station; this took into account direct production costs such as water, electricity, fuel and feed, together with facility depreciation and personal expenses (Anon., 1990). These costs were expected to be the lowest at the present level of juvenile production technologies. Based on these actual release costs, we determined the unit release costs per juvenile at 35 yen for TL 50 mm, 45 yen for 60 mm, 50 yen for 70 mm, 60 yen for 80 mm, 70 yen for 90 mm, 80 yen for 100 mm and 90 yen for 110 mm. We calculated the release costs by multiplying these unit costs by the number of released juveniles.

In 1989 and 1990, TL 20–30 mm groups were released to evaluate the feasibility of releasing small-sized juveniles, but later analysis (described in section **Biological interaction with natural stocks**) revealed that post-release survival rates before recruitment for these releases were quite low, which meant that evaluation of stocking effectiveness including the small-sized groups would be biased. Therefore, we excluded these two small-sized releases from the evaluation.

Contribution of hatchery fish to fishery

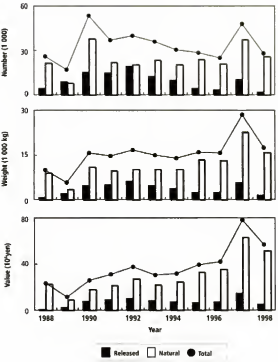
We analysed the fish census data of all landed flounder from June 1988 to May 1999. A total of 368 986 flounder were landed at MFM during this period, of which 106 331 were released and 262 655 were natural. Annual landings of released flounder ranged from 1 779 to 19 415 in number, from 810 kg to 6 366 kg in weight, and from 887 000 to 14 703 000 yen in monetary value. The annual number of landings of natural flounder ranged from 8 020 to 38 109 (Table 2).

The annual number of landings of released flounder increased from 1988 to 1992 but then decreased in 1993. This decrease was considered to be the result of the low survival rates until age 1+ for 1993 and 1994 (Table 3), and introduction of the body length regulation for 1995 and 1996. However, landings of released flounder increased again in 1997 regardless of the discontinuity of releases after 1996. By contrast, landings of natural flounder were relatively stable and ranged from 20 474 to 26 010 except in 1989, 1990 and 1997 (Figure 8, Table 2).

Monthly changes in length frequencies of released flounder landed were determined by age classes based on the mark–recapture information for the high fishing season in Miyako Bay from June to November. The length frequencies of released flounders landed from 1988 to 1995 corresponded to fluctuations in the recruitment months (Figure 9). Age compositions of released flounder landed were estimated from the length frequency data for 132 months from June 1988 to May 1999 (Figure 10). The average composition was 54.4 percent for age 1+, 38.7 percent for 2+ and 6.9 percent for 3+ between 1988 and 1995. The regulation to prohibit catching flounder smaller than TL 30 cm began in July 1995. In 1996, age 2+ and age 3+ fish increased remarkably. Total weight and total value had been increasing since 1995 (Figures 8 and 10). The body length regulation therefore

© Copyright material

FIGURE 8. Annual changes in estimates of landings in number, weight and value for released and natural flounder landed at the Miyako fish market



worked effectively to increase the landings, particularly for weight and value, showing that management of the yield per recruitment is economically efficient.

That there was no age 1+ released flounder in the landings in 1997 was because we had stopped releasing flounder juveniles in 1996. However, we detected age 1+ and 2+ released flounders in the landing (Figure 10, Table 2) in 1998, showing that landings at MFM included hatchery-reared flounders released from other sites, considered to be the southern area of Iwate Prefecture or its northern boundary with Aomori Prefecture. Taking account of these flounders released outside the bay, the number of returned fish was overestimated. However, the number of age 1+ released flounder was negligible, only 58, and that of age 2+ was 461 in 1998. In addition, we excluded from the analysis flounders landed at other fish markets that had been released in Miyako Bay. The numbers of returned flounder were thus not overestimated.

Released flounder were landed with smaller size than TL 30 cm in 1988 and 1989; however, the average total length of released flounder landed became large and stable in the range 31–33 cm between 1990 and 1994. By contrast, that for natural flounder was stable in the range TL 34–36 cm between 1988 and 1994 except 1990. After 1995, the sizes of released and natural flounder landed both increased (TL > 36 cm) as a result of the body length regulation. In 1998, the mean total length of released flounder was 41 cm, larger than that of natural fish, because the age exceeded 3+, which could be judged from the fact that juvenile release was halted in 1996 and 1997 (Figure 11).

The contribution rate for the number of landings was the real value (not estimate) based on the census of all landed flounder at MFM. The average contribution rate for the period of 11 years between 1988 and 1998 was 28.8 percent for the number, 23.4 percent for the weight and 19.4 percent for the monetary value. Released flounder contributed relatively highly to the total landings in each category (Figure 12, Table 2).

The contribution rate ranged from 6.4 percent to 52.7 percent for number, from 8.2 percent to 38.1 percent for weight and from 3.8 percent to 29.9 percent for amount, varying with the survey year. Values rose sharply in 1989 and maintained high levels until decreasing again in 1995 (Figure 12). The rise in 1989 was caused directly by a decrease in landings of natural flounder. The decreased contribution rates in 1995 and 1996 were thought to be caused by the decreased catch of small-sized fish (which made up the majority of the released flounder) as a result of the body length regulation. In 1997, the contribution rates rose again owing to an increase of landings for age 2+ flounders released in 1995 (Figure 10). The contribution rates in 1998 decreased because of the halts to releases in 1996, 1997 and 1998.

FIGURE 9. Monthly changes in age composition of released flounder landed at the Miyako fish market from 1988 to 1995. Length frequencies were divided into three age classes of age 1+, age 2+ and age 3+ or older

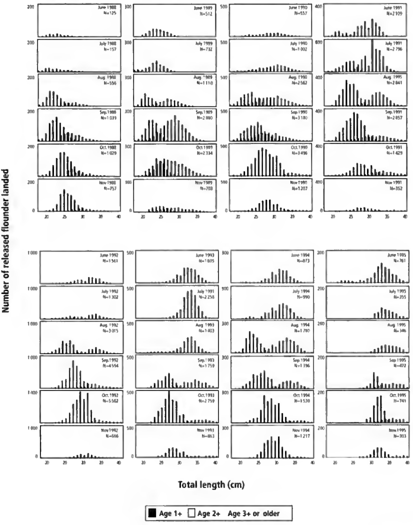


TABLE 3. Estimated numbers of returned released flounder in Miyako Bay

Year of release	No. released	No. returned			Total returned	Return rate (%)
		1+	3+	3+		
1987	157 000	3 448	5 143	702	9 293	5.9
1988	145 000	2 751	5 605	1715	10 071	6.9
1989	69 000	9 004	5 994	1112	16 110	23.3
1990	80 000	7 214	4 808	728	12 750	15.9
1991	96 000	13 495	6 645	643	20 783	21.6
1992	64 000	5 064	3 426	244	8 734	13.6
1993	100 000	5 982	2 403	743	9 128	9.1
1994	80 000	2 052	2 445	2 313	6 810	8.5
1995	60 000	530	8 365	1 260	10 155	16.9
Total	851 000	49 540	44 834	9 460	103 834	(12.2)

TABLE 4. Estimated returns in weight of released flounder in Miyako Bay

Year of release	Weight returned (kg)			Total returned (kg)	Yield/release (g)
	2+	2+	3+		
1987	533	1 288	643	2 464	15.7
1988	385	2 023	1 218	3 626	25.0
1989	1 976	2 349	882	5 207	75.5
1990	1 511	2 027	665	4 203	52.5
1991	3 456	2 864	689	7 009	73.0
1992	1 176	1 417	305	2 898	45.3
1993	1 576	1 361	972	3 909	39.1
1994	832	1 292	1 871	3 995	49.9
1995	204	3 969	1 215	5 388	89.8
Total	11 649	18 590	8 460	38 699	45.5

FIGURE 10. Change in age composition of released flounder landed at the Miyako fish market

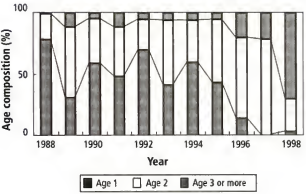
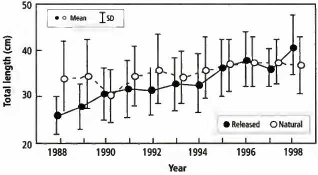


FIGURE 11. Annual changes in the average size at landing for released and natural flounder



Return rates and economic efficiency

We estimated the return rate, the weight of landings of released fish, and the economic efficiency for the nine annual releases from 1987 to 1995 (Tables 3, 4 and 5).

Return rates for the 1987 and 1988 releases were 5.9 percent and 6.9 percent, respectively. Those for the four releases from 1989 to 1992 improved and ranged from 13.6 percent to 23.3 percent. The average return rate of the latter four releases was 18.9 percent, which was about three times as large as the average of 6.4 percent for the former two releases. Return rates for the 1993 and 1994 releases were stable but relatively low. However, the return rate for the 1995 release improved again as a result of the increase of age 2+ fish (Table 3).

The weight of landings obtained from each release group ranged from 2 464 kg to 7 009 kg. The yield per release ranged from 15.7 to 89.8 g with the average of 45.5 g. The body length regulation had a dramatic effect on the 1995 release, resulting in the highest yield per release at 89.8 g (Table 4).

FIGURE 12. Changes in contribution rate of released flounder to total landings by number, weight and value

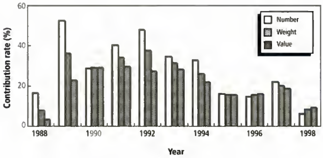
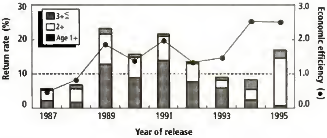


FIGURE 13. Changes in estimated return rate by age class and the economic efficiency for the nine releases from 1987 to 1995



The estimated value of landings for each release ranged from 4 341 000 to 13 596 000 yen. For the 1987 and 1988 releases, with low return rates, the economic efficiency fell below the break-even point. By contrast, for the five release groups from 1989 to 1993 with an improved return rate, the value of the returns exceeded the release costs and the economic efficiency ranged from 1.34 to 1.96. Furthermore, the economic efficiency for the two releases of 1994 and 1995 reached 2.53 and 2.52, respectively, owing to the increase of age 2+ and age 3+ fish in the landings as a result of the size limitation (Table 5, Figure 13).

The relationship between estimated return rates and economic efficiencies for the seven releases from 1988 to 1993 revealed a positive correlation ($R^2 = 0.79$). Economic efficiency thus generally depended on the return rate. Economic efficiencies for the 1994 and 1995 releases were stable at the higher level regardless of the return rate, showing that the body length regulation increased economic efficiency (Figure 14).

TABLE 5. Release cost, estimates of landing value (1000 yen) from released flounder and economic efficiency in Miyako Bay

Year	Release cost	Landing value			Total value	Ecomonic efficiency
	(A)	1+	2+	2+	(B)	(B/A)
1987	9 420	475	1 553	2 313	4 341	0.46
1988	8 700	331	3 393	3 478	7 202	0.83
1989	4 830	1 890	4 273	2 841	9 004	1.86
1990	5 600	1 434	4 052	2 236	7 722	1.38
1991	5 760	3 328	5 366	2 613	11 307	1.96
1992	3 840	1 070	2 656	1 432	5 158	1.34
1993	6 000	1 666	3 517	3 681	8 864	1.48
1994	4 000	1 230	2 878	6 010	10 118	2.53
1995	5 400	285	8 693	4 618	13 596	2.52
Total	53 550	11 709	36 381	29 222	77 312	(1.44)

DISCUSSION

Stocking variables affected the return rates

Scatter plots for the average size at release and return rates showed no linear relationship, suggesting that causes other than size at release affected the return rates (Figure 15).

FIGURE 14. Relationship between return rate and economic efficiency for seven releases from 1987 to 1993. Two releases (1994 and 1995) were outwith the linear relationship with high economic returns because of contributions from fishery management. The numbers against the symbols are the year of release

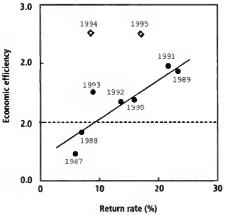
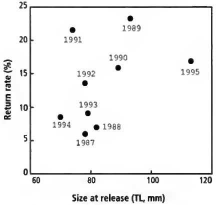


FIGURE 15. Relationship between sizes at release and return rates for nine releases from 1987 to 1995. The numbers against the symbols are the year of release

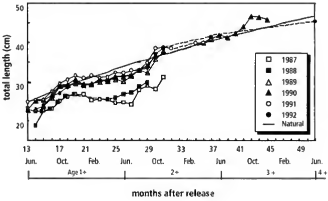


Quality of juveniles

In the juvenile production process, the JASFA Miyako Station selected juveniles of delayed growth to make their length uniform and to prevent cannibalism. Selected juveniles of delayed growth were reared in separate tanks. Only juveniles of normal growth were released from 1989 to 1992, whereas many juveniles of delayed growth were released in 1987 and 1988. The distribution of sound juveniles to Members of the JASFA took first priority and juveniles of normal growth were distributed to several Prefectures in 1987 and 1988. The size at release for 1987 and 1988 were almost the same as for releases from 1989 to 1992; however, time at release became later because the rearing period was extended as a result of the delayed growth (Figure 6, Appendix 2).

We observed clear seasonal growth changes of released flounder, with a period of growth between June and December and a period of no growth from January to May. The releases of 1987 and 1988 were evidently inferior in terms of growth to other groups. By contrast, the releases from 1989 to 1992 showed growth patterns almost equivalent to that of natural flounder populations (Kitagawa *et al.*, 1994; Figure 16). This result showed that flounder juveniles of TL 80 mm released in Miyako Bay in late August or early September could grow to TL 26–27 cm one year after release, 32–37 cm after two years and 40–45 cm after three years. We considered the quality of juveniles caused the difference in return rate of releases from 1987 to 1992. The juveniles of delayed growth released in 1987 and 1988 might have problems related to an inability to survive and lack of physical strength that could directly affect the return rate. Therefore, we concluded that the juveniles of

FIGURE 16. Growth patterns of released flounder for six releases from 1987 to 1992. The mean total length of released flounder estimated from marked fish was plotted along with the growth curve of natural flounder, which was the average of females and males calculated by using the growth curves of Kitagawa *et al.* (1994)



delayed growth in the larval rearing process were inferior in terms of survival and growth rates after release. Judging from the relatively high return rates and similar growth curves to natural flounder, the four releases from 1989 to 1992 were concluded to be of good quality.

Time at release

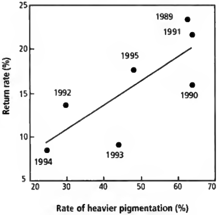
Fujita, Mizuno and Nemoto (1993) pointed out through their surveys in Fukushima Prefecture that delayed releases in a period of lower water temperature slowed growth and lowered the return rate of the released flounder. A comparison of time at release in each group at Miyako Bay showed a difference of two weeks between the releases of 1990–1992 (high return rate) and those of 1987 and 1988 (low return rate). However, there was no distinct difference in the time at release between the 1989 release (high return rate) and those of 1987 and 1988 (low return rate). There was no difference between releases from 1989–1992 and 1995 (high return rate) and those of 1993 and 1994 (low return rate).

Disappearance of black pigmentation

The low return rates for releases of 1993 and 1994 could not be explained by the above analysis. The environmental conditions of the released area could have changed but we have no data to discuss this further. We examined the possibility of the disappearance of the pigmentation on the abocular side. We classified the level of pigmentation of hatchery-produced juveniles using five grades (G1–G5) as follows: G1, an individual with no pigmentation that was impossible to distinguish from natural fish, and that had not been observed in the juvenile production process at Miyako station; G2, an individual with extremely slight pigmentation that could be distinguished from natural fish by careful observation; G3, an individual with a mid level of pigmentation that covered less than 50 percent of the abocular side; G4, an individual with a distinct level of pigmentation that covered more than 50 percent of the abocular side; and G5, an individual with pigmentation covering the entire abocular side.

The relationship between the estimated return rate and the rate of juveniles for G3, G4 and G5 to the sample size was examined for the releases from 1989 to 1995 for normal growth juveniles. A positive correlation was detected, suggesting that the pigmentation may disappear with time ($R^2 = 0.63$, Figure 17). The inspector carrying out this inspection was well trained and had a long experience, so no oversights were expected. The low return rates for the 1993 and 1994 releases were considered to underestimates resulting from a slight disappearance of the pigmentation.

FIGURE 17. Relationship between rate of juveniles with heavier pigmentation than G3 and return rate for seven releases from 1989 to 1995. The numbers against the symbols are the years of release



Post-release survival rate

Because the number of setnets and fishers who operated gillnets and longlines in this area had not varied largely during the period of the survey, the catch pressure on each release was assumed to be constant. The dispersal pattern of each release was stable because few released flounder moved out of the fishing ground around Miyako Bay. The natural mortality rate of each release was considered to be constant after the recruitment when the released fish grew to TL 20 cm. The difference in return rates among releases was considered heavily dependent on the post-release survival rates before recruitment when we neglected the pigmentation problem mentioned above. The quality of juveniles, the time at release and the size at release could all affect the post-release survival rates.

Size at release

We compared the return rates for releases of 1989, 1991, 1992 and 1993 with different sizes at release as distinguished by the ALC or brand marking in order to clarify the relationship between the size at release and the return rate (Appendix 2). We compared the return rates at age 1+ for each release group because it appeared difficult to distinguish release groups for three years after release as a result of shedding of brand marks. In addition, we found a positive correlation ($R^2 = 0.91$) between the return rate at age 1+ and that for the total landings from age 1+ to age 3+ for the releases from 1989 to 1992. We used the releases from 1989 to 1992 for a trial calculation because these releases were not affected by the body length regulation without regard to the underestimation of the return rate caused by disappearance of the pigmentation.

We sampled age 1+ released flounder landed at MFM for six months from June to November and estimated the returns of each release group with a different size at release by identifying their ALC and brand marks. We sampled flounder smaller than TL 30 cm to sample age 1+ fish with certainty and calculated the rate of number of landings for each release group against the sample size. The total number of age 1+ fish returned from the specific release group was estimated by multiplying the rate of each release group by the previous estimates of the total number of landings of age 1+ flounder.

TABLE 6. Estimated return rates at age 1+ for different sizes at release. Release groups were identified by brand and ALC marking

Year of release	Size at release (TL)		No. released (×1000)	No. of returns at age 1+	Return rate at age 1+ (%)
	Class (mm)	(Actual mean) (mm)			
1989	25	23.9	439.0	392	0.1
	60	69.0	25.0	1 879	7.5
	110	107.0	44.0	6 733	15.3
Total			508.0	9 004	
1991	60	62.0	44.0	4 060	9.2
	80	84.1	52.0	9 435	18.1
Total			96.0	13 495	
1992	60	60.0	24.0	875	3.7
	90	88.0	40.0	4 189	10.5
Total			64.0	5 064	
1993	60	60.1	50.0	2 343	4.7
	100	98.7	50.0	3 639	7.3
Total			100.0	5 982	

The release size classes in each year were TL 25, 60 and 110 mm in 1989, TL 60 and 80 mm in 1991, TL 60 and 90 mm in 1992, and TL 60 and 100 mm in 1993. In this experiment, we treated TL 60 mm as a standard size. The difference between actual sizes at release and the size classes ranged from –3.0 to +9.0 mm.

Estimates of the return rate at age 1+ from different sizes at release ranged from 0.1 to 18.1 percent. The return rate became higher with larger release size (Table 6). We calculated the ratio of the return rate for each group to that of the TL 60 mm group in each year. The return rate of the TL 80 mm release was 1.96 times larger than that of the TL 60 mm group, 2.87 times for TL 90 mm, 1.55 times for TL 100 mm and 2.03 times for TL 110 mm (Table 7). The largest ratio was 2.87 for the TL 90 mm group and the ratio decreased when the size at release exceeded TL 100 mm. By contrast, the ratio of the return rate of the TL 25 mm group to that of the TL 60 mm group was about 0.01. We concluded that the most efficient size at release was TL 90 mm. This was in agreement with the result of the otolith marking study, which showed that the survival rate

TABLE 7. Ratio of the return rate for six release groups with different sizes at release to the return rate of the 60-mm size group for each year. The percentage in parentheses shows the return rate at age 1+ for each group given in Table 6

Year of release	Size class at release (TL)					
	25 mm	60 mm	80 mm	90 mm	100 mm	110 mm
1989	0.01	1.00				2.03
	(0.1%)	(7.5%)				(15.3%)
1991		1.00	1.96			
		(9.2%)	(18.1%)			
1992		1.00		2.87		
		(3.7%)		(10.5%)		
1993		1.00			1.55	
		(4.7%)			(7.3%)	

FIGURE 18. Monthly changes in body length frequencies of natural flounder landed at the Miyako fish market from 1988 to 1995

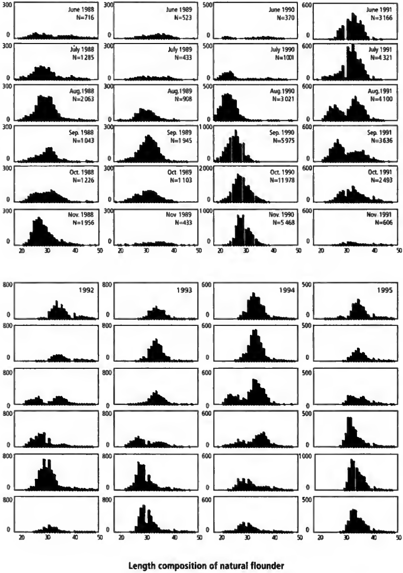
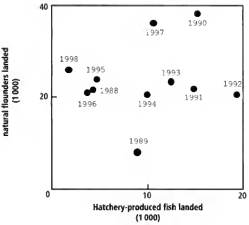


FIGURE 19. Relationship between annual numbers of hatchery-produced and natural flounders landed at the Miyako fish market. The numbers against the symbols are the survey year



of flounder juveniles larger than TL 90 mm at release was relatively high and they were successfully recruited to commercial fisheries (Yamashita *et al.*, 1994).

Biological interaction with natural stocks

The average body length of natural flounder was small in 1990 when landings of natural flounder increased remarkably (Figure 11). No age determination of the natural flounders was carried out, and their age composition was unknown. Body length frequencies of natural flounder, however, showed that age 1+ fish was dominant in the landings (Figure 18). In addition, the distributions of the frequencies for August and September in 1990 suggested shorter body lengths of age 1+ fish than other years. The small average body weight in 1990 was considered to be the result of the large number of age 1+ fish, and the smaller body length to suggest a density effect. However, displacement of natural fish by hatchery fish may not have occurred as judged from the largest number of landings (Table 2).

No positive correlation was observed between the number of hatchery-produced fish and that of naturally produced fish in the landings (Figure 19). This showed that the number of landings of natural flounder was stable except for 1989, 1990 and 1997, regardless of the release numbers (Figure 8). The outstanding landings of natural flounder in 1990 and 1997 might be the result of unusually advantageous environmental conditions such as the high abundance of mysids in 1989 and 1996 when recruited flounders grew in the bay. The decrease in the landings of natural flounder in 1989 was caused by poorer environmental conditions in 1986, 1987 and 1988. The numbers of released fish were 116 800 in 1986, 157 000 in 1987 and 145 000 in 1988, these being the three highest numbers during the survey period (Appendix 2). The numbers of age 1+ fish returned were 3 448 from the release in 1987 and 2 751 from the release in 1988 (Table 3), showing the low survival rates of the released fish, although these values were heavily dependent upon the quality of juveniles as mentioned in section **Stocking variables affected the return rates**. There remained the possibility of the displacement of natural fish by the large numbers of releases from 1986 to 1988. Other releases however, were considered not to have displaced natural fish and to have augmented fishery production. It was considered appropriate to limit the number of released fish below 100 000, although this capacity might vary among years depending upon environmental conditions.

CONCLUSIONS

General lessons

We confirmed the return rates for the nine releases of flounder juveniles between 1987 and 1995 in Miyako Bay, which ranged from 5.9 to 23.3 percent (average 12.2 percent). The yield per release ranged from 15.7 to 75.5 g but was raised to 89.8 g in 1995 by introducing a body size regulation. The economic efficiency was also verified, and ranged from 0.46 to 2.53. We found that the flounder release was economically feasible when we released sound juveniles in August and early September.

The success of stock enhancement essentially depended upon the post-release survival rate, which was considered to have seriously affected the return rate. Quality of juveniles and the carrying capacity were also considered essential for success. Large-sized juveniles were advantageous in obtaining high return rates. The most efficient size at release was detected at TL 90 mm. The release of delayed-growth juveniles in rearing tanks resulted in lower return rates, suggesting that the size selection procedure in the juvenile production process to obtain high survival rates was not the most efficient method. Cost reduction for juvenile production was still required to improve economic efficiency, although production costs have been reduced extensively at the JASFA Miyako Station.

The stocking programme has raised the awareness among fishers for conservation of small fish, and this enabled successful implementation of a body length regulation prohibiting catching flounder below TL 30 cm. The fishing regulation worked effectively both for hatchery and natural flounder and improved the yield per release/recruit efficiently.

The juvenile releases of flounder augmented the fishery production. The augmentation was restricted by the carrying capacity of the release site and habitat.

Strength and weakness of the programme

The strength of the programme was that it allowed us to verify the stocking effectiveness scientifically by introducing the fish census at the fish market. Appropriate stocking variables such as release sites, release timings and sizes at release were also considered. The intrageneration effectiveness of stocking was thus evaluated; however, it was unclear whether released fish supplemented the reproduction of the wild stock. Flounder juveniles had been released over all of the fishing grounds in Iwate Prefecture, but we could not compare catch trends of flounder between areas with and without releases. The recent landings of naturally produced flounder in Miyako Bay increased in 1997 and 1998 (Figure 8) and the annual catch of flounder for whole of the Iwate Prefecture reached an historical high in 1997 (Figure 3). A remarkable increase in annual catch has been observed since 1996 in the northern Pacific Ocean where 20 percent of the annual number of flounder released in Japan are concentrated. This increasing trend was also shown elsewhere, except in two areas of the Sea of Japan (Figure 1).

Genetic effects on wild stocks have not been investigated. The only possible precautionary measure would be to develop the technology capable of producing fish genetically close to those of wild stocks. Broodstocks were replaced by natural flounders both in 1997 and in 2000. Tests of genetic similarity between wild and hatchery-produced juveniles and longitudinal monitoring of the genetic structure of the wild stocks will be required (Kitada, Hayashi and Kishino, 2000).

Future prospects and limitation

The JASFA began releasing flounder again in 1999 to examine the rate of disappearance of the pigmentation on the abocular side in the natural environment. The numbers of flounder released were 40 000 in 1999 and 2000, and a release of 100 000 juveniles was scheduled for 2001. All flounders were marked on otoliths with ALC. The fish census at MFM has been continued.

Annual landings of released flounder at MFM were not large, ranging from 810 to 6 366 kg in weight and 887 to 14 703 thousand yen in monetary value. By contrast, landings of natural flounder at MFM were large, ranging from 3 568 to 22 662 kg in weight and 8 782 to 63 077 thousand yen in value, and these numbers had increased and stayed at a high level despite the unexpected discontinuation of releases since 1996 as a result of disease problems. It may not be possible to increase the landings of hatchery flounder beyond the present level because of the ceiling of the carrying capacity in the bay. Stopping releases and monitoring the number of landings and the age composition were considered appropriate. When the landings decrease, stocking could be considered as an option of the adaptive management procedure, in which technologies for juvenile production should be maintained during the moratorium.

The goal of stock enhancement has been to obtain high yield per release, which should be changed to maintain fishery production while conserving wild stocks. Of most importance is to reconsider the necessity of stocking programmes by taking the status of stocks and fisheries into account. Rationality for stock enhancement is demanded.

References

Anon. 1990. *1987 Annual Report.* Tokyo, Japan Sea-Farming Association. (in Japanese.)

Anon. 2000a. *1998 Statistics for Production and Release of Juveniles in Japan.* Tokyo, Japan Sea-Farming Association. (in Japanese.)

Anon. 2000b. *1998 Statistics for Fisheries and Aquaculture Production in Japan.* Tokyo, Fisheries Agency. (in Japanese.)

Asahida, T., Saitoh, K., Yamashita, Y., Aonuma, Y. & Kobayashi, T. 1998. Genetic variation in the Japanese flounder based on analysis of mitochondrial DNA by restriction endonucleases. *Nippon Suisan Gakkaishi*, 64: 377–383. (in Japanese.)

Bartley, D.M., Kent, D.B. & Drawbridge, M.A. 1995. Conservation of genetic diversity in a white seabass hatchery enhancement program in southern California. *In* H. L. Schramm Jr & R. G. Piper, eds. *Uses and effects of cultured fishes in aquatic ecosystem. American Fisheries Society Symposium*, 15: 249–258.

Fujita, T., Mizuno, T. & Nemoto, Y. 1993. Stocking effectiveness of Japanese flounder *Paralichthys olivaceus* fingerlings released in coast of Fukushima Prefecture. *Saibai Giken*, 22: 67–73. (in Japanese.)

Harada, Y., Yokota, M. & Iizuka, M. 1998. Genetic risk of domestication in artificial stocking and its possible reduction. *Res. Pop. Ecol.*, 40: 311–324.

Imamura, K. 1999. The organization and development of sea farming in Japan. *In* B. R. Howell, E. Moksness & T. Svåsand, eds. *Stock enhancement and sea ranching*, pp. 91–102. Oxford, UK, Fishing News Books, Blackwell Science Ltd. 606 pp.

Kitada, S. 1999. Effectiveness of Japan's stock enhancement programmes: current perspectives. *In* B. R. Howell, E. Moksness & T. Svåsand, eds. *Stock enhancement and sea ranching*, pp. 103–131. Oxford, UK, Fishing News Books, Blackwell Science Ltd. 606 pp.

Kitada, S., Hayashi, T. & Kishino, H. 2000. Empirical Bayes procedure to estimate genetic distance between populations and effective population size. *Genetics*, 156: 2063–2079.

Kitada, S., Taga, Y. & Kishino, H. 1992. Effectiveness of a stock enhancement program evaluated by a two-stage sampling survey of commercial landings. *Can. J. Fish. Aquat. Sci.*, 49: 1573–1582.

Kitagawa, D., Ishito, Y., Sakurai, Y. & Fukunaga, T. 1994. Age, growth and maturation of the Japanese flounder *Paralichthys olivaceus* in coastal waters of the northern Sanriku District. *Bull. Tohoku Natl Fish. Res. Inst.*, 56: 69–76. (in Japanese.)

Kojima, H. 1995. Evaluation of abalone stock enhancement through the release of hatchery-reared seeds. *Mar. Freshwater Res.*, 46: 689–695.

Kuwada, H. & Tsukamoto, K. 1987 Marking of red sea bream *Pagurus major* larvae by alizarin comprexone (ALC) of otoliths. *Saibai Giken*, 16: 93–104. (in Japanese.)

Miyakoshi, Y., Nagata, M., Sugiwakam, K. & Kitada, S. 2001. Commercial harvest of hatchery-reared masu salmon *Oncorhynchus masou* smolts estimated by a coast-wide sampling program in Hokkaido, northern Japan, and the two-stage sampling schemes of landings. *Fish. Sci.*, 67: 126–133.

Okouchi, H., Kitada, S. & Iwamoto, A. 1998. A method for estimating age composition of released fish using information from tag recoveries. *Nippon Suisan Gakkaishi*, 64: 462–468. (in Japanese.)

Tanaka, M., Ohokawa, T., Maeda, T., Kinoshita, I., Seikai, T. & Nishida, M. 1997. Ecological diversities and stock structure of the flounder in the Sea of Japan in relation to stock enhancement. *Bull. Natl Res. Inst. Aquacul., Suppl.*, 3: 77–85.

Yamada, H., Nagahara, S., Sato, K., Musashi, T., Fujita, T., Nihira, A., Kageyama, Y., Kumagai, A., Kitagawa, D., Hirota, Y. & Yamashita, Y. 1994. Species composition and distributional pattern of misidacea in Pacific Ocean coast of Japan. *Bull. Tohoku Natl Fish. Res. Inst.*, 56: 57–68. (in Japanese.)

Yamada, H., Sato, K., Nagahora, S., Kumagai, A. & Yamashita, Y. 1998. Feeding habits of Japanese flounder *Paralichthys olivaceus* in Pacific coastal waters of Tohoku District, northeastern Japan. *Nippon Suisan Gakkaishi*, 64: 249–258. (in Japanese.)

Yamashita, Y., Nagahara, S., Yamada, H. & Kitagawa, D. 1994. Effects of release size on survivial and growth of Japanese flounder *Paralichthys olivaceus* in coastal waters off Iwate Prefecture, northeastern Japan. *Mar. Ecol. Prog. Ser.*, 105: 169–176.

Appendix 1

CAPTIVE BROODSTOCKS OF FLOUNDER AT JASFA MIYAKO STATION

Year	Number		Mean TL (range) cm		Mean BW (range) kg		Age	
1987	–	167	48.0	(31.4–66.5)	2.1	(0.4–3.9)	Natural	3–9
							Hatchery	4–7
1988	_	18	60.0	(54.2–70.7)	3.5	(2.5–5.0)	Natural	3–10
	_	67	46.1	(35.2–67.0)	1.3	(0.6–3.8)	Hatchery	5–8
	–	83	45.5	(31.5–62.2)	1.3	(0.4–3.9)		
Total or mean		168	47.3	(31.5–70.7)	1.5	(0.4–5.0)		
1989	_	42	59.0	(44.5–74.0)	2.9	(1.2–5.3)	Natural	4–11
	_	133	50.2	(39.0–72.0)	1.6	(0.8–3.8)	Hatchery	6–9
Total or mean		175	52.3	(39.0–74.0)	1.9	(0.8–5.3)		
1990	_	33	61.7	(47.0–73.0)	3.7	(1.5–5.9)	Natural	5–12
	_	61	53.5	(41.5–72.0)	2.2	(1.2–4.4)	Hatchery	3–10
	–	18	56.8	(49.0–65.5)	2.9	(2.0–4.4)		
Total or mean		112	56.5	(41.5–73.0)	2.7	(1.2–5.9)		
1991	_	39	–		–		Natural	6–13
	_	69	–		–		Hatchery	4–11
Total or mean		108	60.3	(45.0–77.0)	3.2	(1.4–6.6)		
1992	_	37	–		–		Natural	7–14
	_	68	–		–		Hatchery	5–12
Total or mean		105	60.7	(48.0–77.0)	3.3	(1.4–6.6)		
1993	_	36	75.6	(70.0–82.0)	6.4	(4.6–8.3)	Natural	8–15
	_	67	55.6	(49.0–61.0)	2.2	(1.3–2.9)	Hatchery	6–13
Total or mean		103	62.6	(49.0–82.0)	3.7	(1.3–8.3)		
1994	_	43	–		–		Natural	9–16
	_	67	–		–		Hatchery	7–14
Total or mean		110	63.2	(48.0–85.0)	4.2	(1.2–8.6)		
1995	_	43	82.7	(75.0–95.0)	8.2	(5.3–10.0)	Natural	10–17
	_	110	58.3	(51.0–83.0)	2.5	(1.4–2.8)	Hatchery	8–15
Total or mean		153	67.8	(51.0–95.0)	4.8	(1.4–10.0)		
1996	_	78	64.5	(59.0–75.0)	2.8	(2.2–3.8)	Natural	2,3
	_	79	48.9	(43.0–54.0)	1.3	(0.9–1.6)	Hatchery	9,10
Total or mean		157	56.7	(43.0–75.0)	2.0	(0.9–3.8)		
1997	_	21	43.5	(36.0–56.0)	0.9	(0.3–2.0)	Natural	2–4
	_	7	38.2	(32.0–52.0)	0.6	(0.4–0.9)		
Total or mean		28	42.2	(32.0–56.0)	0.8	(0.3–2.0)		
1998	_	14	47.5	(37.0–60.0)	1.8	(0.5–3.2)	Natural	5–6
	_	15	41.7	(35.0–48.0)	0.9	(0.5–1.3)		
Total or mean		29	44.5	(35.0–60.0)	1.3	(0.5–3.2)		

Appendix 2

JUVENILE RELEASES OF FLOUNDER BY JASFA MIYAKO STATION

Year	Release site	Normal size (TL40 mm and over)				Small size (TL40mm under)		
		Number (×1000)	Mean TL (range) mm	Month	Marking method (Marking rate, %)	Number (×1000)	Mean TL (range) mm	Marking method (Marking rate, %)
1980	Miyako Bay					245.0	25 (13–30)	–
Total or mean		–	–	–	–	245.0	25 (13–30)	0.0
1981	Taro Bay	13.0	71 (55–88)	Sep.	–			
		11.0	76 (62–93)		–			
		15.0	77 (58–95)		–			
		11.0	94 (72–120)	Oct.	–			
		50.0	79 (55–120)		(0.0)	–	–	–
1982	Miyako Bay	20.0	130 (100–150)	Oct.	Disk tag			
		50.0	100 (95–120)		–			
	Taro Bay	10.0	130 (100–150)		Disk tag			
		13.0	100 (95–120)		–			
	Sakiyama	2.0	140 (100–160)		Anchor tag			
Total or mean		95	110 (95–160)		(33.7)	–	–	–
1983	Taro Bay	25.0	144 (90–174)	Oct.	Disk tag			
		1.0	120 (90–150)		Fin clipping			
		4.0	131 (90–150)		–			
		4.8	180 (120–220)		Disk tag			
	Sakiyama	18.0	120 (90–150)		–			
		13.0	40 (30–55)		Laser			
		3.7	190 (170–220)	Nov.	Anchor tag			
Total or mean		69.5	114 (30–174)		(68.3)	–	–	–
1984	Taro Bay	7.0	165 (130–220)	Oct.	Disk & Laser			
		5.0	150 (120–220)		Disk tag			
		5.0	188 (150–230)		Ribbon & Laser			
	Sakiyama	2.9	162 (100–220)	Nov.	Anchor, Disk			
		2.0	70 (50–90)		–			
Total or mean		21.9	157 (50–230)		(23.0)	–	–	–
1985	–	–	–	–	–	–	–	–
1986	Miyako Bay	46.0	52 (36–64)	Sep.	Ratex			
		3.0	51 (44–63)	Oct.	–			
		37.8	81 (42–136)		Ratex			
		30.0	98 (74–126)		Ratex & Laser			
Total or mean		116.8	73 (36–136)		(97.4)	–	–	–
1987	Miyako Bay	74.0	84 (62–111)	Sep.	Ratex			
		64.0	62 (42–79)		–			
		19.0	107 (90–141)		Ratex			
Total or mean		157.0	78 (42–141)		(59.2)	–	–	–

Year	Release site	Normal size (TL40 mm and over)				Small size (TL40mm under)		
		Number (×1000)	Mean TL (range) mm	Month	Marking method (Marking rate, %)	Number (×1000)	Mean TL (range) mm	Marking method (Marking rate, %)
1988	Miyako Bay	126.0	82 (41–107)	Aug.	Ratex			
		9.0	43 (29–78)		–			
		10.0	120 (108–134)	Oct.	Disk tag			
Total or mean		145.0	82 (29–134)		(93.8)	–	–	–
1989	Miyako Bay	25.0	69 (45–82)	Aug.	Brand	323.0	21 (16–30)	ALC
		44.0	107 (91–123)	Sep.		116.0	32 (26–37)	
Total or mean		69.0	93 (45–123)		(100.0)	439.0	24 (16–37)	(100.0)
1990	Miyako Bay	54.0	81 (56–100)	Aug.	Brand	194.0	25 (24–33)	ALC
		26.0	107 (95–121)					
Total or mean		80.0	89 (45–123)		(100.0)	194.0	25 (24–33)	(100.0)
1991	Miyako Bay	44.0	62 (56–72)	Aug.	ALC			
		15.0	82 (66–93)					
		37.0	85 (76–104)		Brand			
Total or mean		96.0	74 (56–104)		(100.0)	–	–	–
1992	Miyako Bay	24.0	60 (40–75)	Aug.	ALC			
		20.0	**89** **(74–109)**					
		20.0	**87** **(76–107)**		**Brand**			
Total or mean		64.0	78 (66–93)		(100.0)	–	–	–
1993	Miyako Bay	50.0	60 (49–76)	Aug.	ALC			
		50.0	99 (85–112)	Sep.	Brand			
Total or mean		100.0	79 (49–112)		(100.0)	–	–	–
1994	Miyako Bay	40.0	58 (47–74)	Aug	ALC			
		40.0	83 (65–102)	Sep.	Brand			
Total or mean		80.0	70 (47–102)		(100.0)	–	–	–
1995	Miyako Bay	30.0	110 (86–125)	Sep.	ALC			
		30.0	117 (85–138)		Brand			
Total or mean		60.0	113 (85–138)		(100.0)	–	–	–
1996	No releases							
1997	No releases							
1998	No releases							

Appendix 3

ESTIMATION OF AGE COMPOSITION OF RELEASED FLOUNDER WITHOUT MARKS

Most flounders landed on the Miyako fish market were age 1+ and age 2+ fish. We treated the remainder as age 3+ including older fish because age 0+ fish were not landed.

Suppose a monthly body length frequency of untagged hatchery fish with unknown age composition and the total number of individuals in the frequency is known as *N*. Let the observed number of fish of length class x_j be n_j ($j = 1, 2, \dots, J$) and the total number of each age class be *Ni* ($i = 1, 2, 3$). We then hold the relationship as

$$N = \sum_{j=1}^{J} n_j = \sum_{i=1}^{3} N_i \, . \tag{1}$$

We estimate *Ni* ($i = 1, 2, 3$) assuming normal distributions for the length frequencies of age 1+ and age 2+ with means of μ_1 and μ_2 and variances of σ_1^2 and σ_2^2. The probability for age *i*+ fish in the *j*th length class is given by

$$p_{ij} = \frac{\Delta x}{\sqrt{2\pi\sigma_i^2}} \exp\left\{ \frac{-(x_j - \mu_i)^2}{2\sigma_i^2} \right\} . \tag{2}$$

where Δ_x is the length class interval. The probability p_{ij} is estimated by substituting the means and variances of age 1+ and age 2+ hatchery fish landed into the Equation (2). A smaller Δ_x provides better accuracy. For length classes larger than mean length of age 2+, length frequencies of age 2+ and 3+ may be highly overlapped. Hence, we first estimate the number of age1+ (N_1) and 2+ (N_2) fish in the total number of individuals in the frequency (*N*) by minimizing the sum of squares

$$SS = \sum_{j=1}^{J} \left(n_j - \sum_{i=1}^{2} N_i \, p_{ij} \right) . \tag{3}$$

The number of individuals of age 3+ fish can be calculated by subtracting the estimates of the total number of individuals of age 1+ and 2+ from the total number of individuals in the frequency.

To estimate the weight of the landings by using a length–weight relationship, the number of age *i*+ fish in the *j*th length class ($= n_{ij}$) is required, which is estimated by using the estimate of N_i for the length classes of μ_2 and smaller as

$$\hat{n}_{ij} = \frac{\hat{N}_i \hat{p}_{ij}}{\sum_{i=1}^{2} \hat{N}_i \hat{p}_{ij}} \times n_j \, . \tag{4}$$

For length classes larger than μ_2, n_{ij} of age 1+ and 2+ is estimated by

$$\hat{n}_{ij} = \hat{N}_i \hat{p}_{ij} \, . \tag{5}$$

If $(n_{1j} + n_{2j}) > n_j$, n_{ij} is estimated by Equation (4) judging age 3+ fish are not included in the *j*th class. The number of age 3+ fish is estimated by subtracting the number of age 1+ and 2+ fish from the observed number in each class as

$$\hat{n}_{3j} = n_j - \sum_{i=1}^{2} \hat{n}_{ij} \tag{6}$$

Summary of case studies on the effectiveness of stocking aquacultured fishes and invertebrates to replenish and enhance coastal fisheries

Kenneth M. Leber
Director, Center for Fisheries Enhancement,
Mote Marine Laboratory, Sarasota, FL 34236, United States of America

INTRODUCTION

With coastal fisheries in decline around the world, there is mounting concern about how long current sources of seafood can supply world needs. Governments, resource managers and those who make their livelihood on fishing are seeking better ways to improve fishing yields. Many seek greater emphasis on restocking and aquaculture-based stock enhancement as a way rapidly to replenish depleted fish stocks and increase fishery landings. How to focus fishery-management resources so that priorities can be placed on successful management strategies is a crucial issue for the nations of the world that rely on seafood.

A look at any current textbook on fisheries science will show that there is little, if any, insight about how to make stocking an effective fishery-management tool in open-water coastal ecosystems (oceans, seas and estuaries). Currently, there is great debate among fishery scientists about whether stocking cultured fishes and invertebrates is an economically sound way to improve coastal fisheries (e.g. Blankenship and Leber, 1995; Hilborn, 1998, 1999; Blaxter, 2000). Yet many new sea ranching programmes are being planned, even as more and more people realize that there are very few successful examples of cost-effective stock enhancement of coastal stocks anywhere in the world.

Why, then, do coastal stocking programmes continue after more than a century of stocking aquacultured marine organisms in Asia, Europe and North America with little clear evidence of success? Stocking persists for two basic reasons: it is an attractive approach to fishermen and the public for increasing fishery landings; and until recently there was little if any evidence that could be used to evaluate the effectiveness, or lack thereof, of stocking coastal waters to improve fishery landings. Without much evidence to the contrary about stocking effectiveness, hatchery advocates have consistently been able to gain political support for funding large stocking programmes.

THE CASE STUDIES

In this volume, detailed overviews are presented on case studies that represent a range of marine ranching situations. These contributions represent what scientists and resource managers from several nations have found about stocking effectiveness, upon close examination of the efficacy of some of their regions' best examples of sea ranching (release of hatchery-reared animals into the sea to increase fishery landings). This volume presents, for the first time, a compilation of the goals, rationale, approach, assessment and needs of sea ranching from several different geographical areas of the world. What these papers show us is that stocking can clearly work in some cases to increase fishery landings, but that economic success will depend on many factors such as the management system, survival, culture costs and how the resource is valued. Sea-ranching technologies and strategies need far more scientific development before stocking can be generally accepted as an economically effective fishery-management tool in coastal regions.

The diversity of organisms and ecosystems covered by the case studies in this volume provide good insight about the current state-of-the-art in the field of stock enhancement and sea ranching. Among the most successful sea ranching programmes in the world are the scallop and marine fish programmes in Japan. The case study included here, which is on Japanese flounder, is one of the best examples anywhere that shows the potential for sea ranching to be an economically effective fishery management tool.

The major scientific effort to develop successful sea ranching of cod in the fiords of Norway shows the importance of carrying-capacity limitations on recruitment processes, which in this case were a barrier to success. However, the Norwegian studies of the effectiveness of stocking European lobster show good potential for successful sea ranching of crustaceans.

Assessment of the contribution of hatchery-released sturgeon by Iran in the landlocked Caspian Sea reveals how important stocking may be for preserving endangered species and for generating income from an extremely valuable fishery product, caviar. Yet the difficulties in managing sturgeon fisheries in the Caspian, especially since the collapse of the former Soviet Union, which helped to regulate the caviar fishery, reinforce our understanding of the clear need to blend sea ranching with other effective fishery-management strategies (good enforcement of fishing regulations and habitat preservation).

Sea Ranching work with barramundi in Australia shows how post-release survival can be maximized using a series of pilot release experiments to define optimal release strategies. The barramundi experience also points to the need to have good control over enhancement protocols already in place when expanding sea ranching from test sites and involving private growers and local communities in sea ranching efforts.

Work to develop a sea cucumber sea ranching technology for small-island developing states in the Pacific is a good example of how many issues one is faced with, and the planning that needs to be conducted, prior to starting new stocking programmes. Through such planning, studies to resolve several limitations that need to be overcome are now under way and many uncertainties will be resolved before much stocking is done.

These case studies are all good examples of how much focus there is today on using a scientific and responsible approach to develop and test sea ranching technologies. They all exemplify the need to use a scientific and adaptive approach to planning and implementing stocking programmes.

REVIEW OF THE FISHERY

It is clear from all of the case studies that fishery harvests over the past 30 years have declined. In some cases, however, the declines are so drastic (beluga sturgeon in the Caspian Sea, sea cucumbers in Chuuk) that there is little hope these stocks will recover on their own.

In many of the case studies, overfishing is clearly a principal problem with the fishery. The case study of sturgeon in the Caspian Sea shows how stocks plummeted, beginning in 1991. Following the collapse of the Soviet Union, it has been difficult to enforce fishery management strategies in the northern Caspian Sea, where strong centralized control over the fishery by a single government was replaced with weak to little control in some of the new nations that were formed, and sturgeon poaching has increased dramatically as a result.

Sea cucumbers in the Pacific and European lobster in Norway are also good examples of how absence of strong regulations and enforcement can result in serious depletion of the fishery. Overharvesting has severely reduced some stocks of sea cucumbers. The boom-and-bust pattern, with three to four decades before stocks could recover to levels where profitable harvests were possible again, made them especially vulnerable to fishing. Management of stocks at high harvest levels is particularly difficult in small-island developing states, which often do not have the financial and human resources needed to enforce management regulations. In the Pacific, emphasis now is on greater awareness and community-based fishery management. In Norway, strict regulations were not developed. Thus, lobster stocks were declining in Norway at the same time that other European nations that enforced tougher catch restrictions were able to maintain relatively stable yields in their lobster fisheries.

By contrast, there are relatively strong fishery management practices for barramundi in Australia, where fishing effort is strongly regulated (except for some recreational fisheries). Consequently, barramundi sea ranching is more likely to be used to enhance stocks only during poor recruitment years and there is less need to replenish depleted stocks.

Troubles for sturgeon fisheries in the Caspian Sea (and barramundi fisheries in Australia) are compounded by development, particularly of dams. Dams have been constructed on all of the great rivers that flow into the Caspian Sea, except for the Ural River. As a consequence, most of the spawning habitat for sturgeon is now inaccessible to fish migrating to spawning grounds. Oil pollution is another major concern in the Caspian Sea.

RATIONALE FOR SEA RANCHING PROGRAMMES

A principal factor that has sparked the use of sea ranching is the long time required for recovery of depleted (recruitment overfished) fisheries if only traditional management measures are used. It can take decades to recover some stocks by decreasing harvest rates and increasing minimum size for harvest. The hope for sea ranching is to be able to increase numerical abundance rapidly by bypassing juvenile recruitment bottlenecks. A prime example of this is sturgeon. Sea ranching was chosen for sturgeon more or less out of necessity, to try to sustain stocks that were fast disappearing, because there was little chance that natural recruitment could reverse declines in fishery landings. Similarly, sea ranching was planned with sea cucumber because of severe recruitment limitations in their coral reef habitats.

Other sea ranching programmes were initiated to enhance fishing opportunities. Barramundi stocking is focused mainly on recreational fisheries and was started to establish impoundment fisheries in waters that otherwise would have had only limited fishing potential. Only in Queensland are barramundi stocked in the sea, in an effort there to develop stocking techniques that can increase abundance of a relatively well-managed stock. Japanese flounder sea ranching was started as part of a large, multispecies, national effort to enhance commercial fisheries. Both depleted and declining stocks were targeted. Likewise, the Norwegian sea ranching programme (PUSH) was started as a national initiative to coordinate development efforts to enhance fishery landings of four species. The intent of the PUSH programme was to assess from a biological point of view the potential for sea ranching in Norway.

In none of the case studies were other fishery management options ignored. For example, in Australia control of fishing effort is the principal management technique. The extreme situation evident in recent attempts to manage sturgeon stocks clearly reflects how important sound regulations, good enforcement and habitat protection all are to maintaining fished stocks. Stocking alone would be no substitute for other management methods and may have little or no effect without them.

METHODOLOGY OF SEA RANCHING

The case studies reveal that clear efforts are now being made to use a responsible approach in developing and applying sea ranching technology, albeit to different degrees. It is notable that a strong scientific approach to developing, testing and evaluating sea ranching potential is now being used in most of the case studies presented here . This follows decades of little or no science available to plan such programmes effectively worldwide. Stocking strategies for sturgeon in the Caspian Sea have been developed since 1955 and now support an active commercial fishery.

To conserve the genetic diversity of wild stocks, broodstock selection and management is a key consideration in sea ranching. Whereas strict protocols are followed in some of the case studies to prevent translocation of exogenous genes and changes in allele frequencies of wild stocks, this is still not a universal practice.

To prevent transferring diseases and parasites to wild stocks, or enhancing disease in the wild, strict controls are needed to ensure that only healthy hatchery-reared organisms are released. There is clear variation among the case studies in the degree of emphasis on evaluating and certifying the health of hatchery organisms prior to release.

Methods for selecting release strategies also varied widely among the case studies. Some regions used controlled experiments to compare effects of release strategies on recapture rates; others have not. There appear to be opportunities to increase post-release survival rates, especially in cases where optimal release strategies have not been identified or followed. For example, "spot stocking", the introduction of stocked fish into receiving waters at the same time, is often used with sturgeon because it is easier than the more desired practices of "scatter stocking", in which fish are introduced into several sites within a region, or "trickle stocking", in which fish are introduced into a given region over a period of time, even though the latter afford better results.

In the sea cucumber studies in the Pacific islands, there has been a concerted effort to understand ecology and life history prior to launching a stocking programme. This programme, based firmly on a responsible approach, exemplifies the trend seen in most of the case studies to use pilot release experiments to optimize release strategies.

MONITORING AND EVALUATION PROGRAMMES

Measures of success

There is much variation among the case studies in the ability to gauge success, largely because of differences in marking and assessment capabilities for identifying stocking contributions to fisheries. Some programmes use high-information content tags to optimize release strategies, others use simply a benign indicator mark that identifies stocked organisms as such but has no additional information. Unfortunately, so far the search for a marking system for sea cucumbers has proved entirely futile. Some of the case studies conduct quantitative assessment, whereas others rely on more casual observations of hatchery contributions to the catch.

The contribution of hatchery fish to fishery landings varied widely in the case studies. However, all of the case studies presented impressive results. Although the actual contribution of stocked sturgeon is slightly unclear, it was evident from the European lobster studies in Norway, and with all of the species tested in the other case studies, that hatchery organisms can make substantial contributions to recruitment in coastal environments (i.e. clearly greater than 10 percent in most cases and often substantially higher).

Although a large hatchery contribution to fishery landings is impressive – it indicates that hatchery fish have survived and entered the fished stock – the more important estimate of success of coastal stocking programmes is the amount of increase in total catch afforded by stocking. But this is much harder to evaluate. Nevertheless, it is essential to determine the effect of stocking on total catch. High fishery contribution rates from stocked fish, coupled with evidence that total catch has not increased from stocking, is an indication that hatchery fish are merely replacing wild individuals. A good example of stocking success, in which total catch has clearly increased from released hatchery organisms, is the scallop fisheries of Hokkaido, Japan, (Honma, 1993). Catch increases to levels well above historic catches were initially based almost entirely on stocked *Patinopectin yessoensis* (Honma, 1993).

The importance of adapting a quantitative assessment procedure to sea ranching programmes

Benign marks that can distinguish hatchery from wild organisms, such as the pigmentation on cultured Japanese flounder and the absence of an olfactory septum in cultured sturgeon, are a valuable assessment tool. Such benign marks provide a simple and inexpensive way to distinguish hatchery from wild stocks and quantify the contribution of stocked fish to fishery yields. However, to understand and achieve their potential, sea ranching programmes need more than a simple benign mark; because there are so many unanswered questions that remain critical uncertainties about how to manage stocking effectiveness, more answers are needed to make sea ranching effective (Leber, 2002).

Many of the case studies require improvements in yield–cost ratio in order to be cost effective. To establish the potential impact of stocking, a mechanism should be deployed to determine if higher yields per stocked fish can be achieved. What is needed is high-information content, benign marks or tags, a critical requirement for adaptive management, to improve results based on experience when questions are posed with each release – an identifying tool that will allow any occasion for stocking to be used to address critical uncertainties about stocking strategies. High-information tags afford a way to perform scientific queries on a range of issues, simultaneously, identifying experimental variables, control conditions and replicates. A key improvement over the sea ranching practices used during most of the twentieth century (prior to the 1990s) is that assessment of stocking contribution was conducted in all of the case studies presented here.

ECONOMIC ANALYSIS (COST/BENEFIT)

Most of the case studies indicated that improvements in yield–cost ratio are needed in order to be cost effective. Release contributions to fishery landings spanned a wide range among the case studies. Except for Japanese flounder and beluga sturgeon, the economics of the other programmes showed that more research is needed before any of them would be economically viable. The case study with Japanese flounder, however, shows the greatest potential for successful sea ranching. There was a strong scientific approach used and clear economic benefits were documented for several Japanese flounder stocking locations. Given the potential for further improvements in post-release survival through adaptive management, after adopting a high-information content tag, the economic benefits already evident could substantially increase.

There were also very promising results with European lobster and barramundi, in part because of the strong scientific approach used by these programmes. Clear economic benefit has not been documented with these species, but it seems achievable if these studies continue to resolve critical uncertainties about stocking. Although carrying capacity constraints were documented with stocked cod, there is clearly some potential for profitability with Atlantic salmon, Arctic char and sea cucumbers given improved survival and growth rates, reduced rearing costs and improvement in market price.

In general, the case studies focusing on marine organisms indicate that sea ranching costs can probably be reduced in the future, as improvements in survival in the hatchery are made as a result of advances in aquaculture technology. There also appears to be latitude for improvement in post-release survival in many of the case studies.

PROBLEMS WITH PAST STOCK ENHANCEMENT PROGRAMMES

The principal problem in coastal stock enhancement programmes during most of the past century has been lack of attention on the results of stocking. Stocking coastal waters to enhance fisheries began in the last two decades of the nineteenth century in Norway, Japan and the United States. In the period that followed and until about the 1970s (for salmonids) and 1990s (for marine species), there had been so little attention given to what was achieved from stocking that even the most rudimentary stocking strategies had not been tested for effectiveness and efficiency.

The emphasis historically in stocking programmes has been on the number of fish stocked, when it should have been on fishery yield per stocked fish, ways to improve that yield and interactions with wild stocks. Why were these key success factors not considered? This was because fishery managers and scientists lacked the basic technologies needed to develop the scientific basis for stocking programmes: (1) a mark or tag to identify small hatchery fish, and (2) the marine aquaculture technology needed to grow advanced juveniles (Blankenship and Leber, 1995). As coastal fishery landings were falling, the pressure to fill stocking quotas only increased. This in turn led to fixation on stocking mostly tiny fish (postlarvae), as the unit cost to produce larger individuals is much greater. Many of the case studies, however, have shown that size-at-release is a critical variable, which can make or break stocking success (e.g. Svåsand *et al.*, Russell and Rimmer, Okouchi and Kitada).

The early stocking programmes were method orientated, not problem orientated. Scientists were not seeking answers to critical uncertainties about post-stocking survival and interactions with wild stocks. In addition, only recently has there been greater acceptance of the process for optimizing stocking strategies – adaptive stocking, in which critical uncertainties about stocking effect are evaluated and ideas for improvement are tested and recycled through the process of strong inference (Baconian science) (Platt, 1964; Cowx, 1994; Blankenship and Leber, 1995; Leber, 1999).

Thus many stocking practices today are not built on a very scientific basis (Leber, 1999). As such, few of the critical uncertainties about stocking effects are actually understood. And there are few good examples of successful stock enhancement or sea ranching. Many stocking programmes still lack an adaptive approach and rely on a relentless interest in numbers stocked to sustain their funding base.

GENERAL CONCLUSIONS AND BROAD LESSONS FROM STOCK ENHANCEMENT AND SEA RANCHING PROGRAMMES

Except for a few specific examples, stock enhancement and sea ranching technology is generally lacking in sufficient information needed to ensure profitability. As the case studies clearly show, using cultured organisms to increase fishery landings is not straightforward and entails much more than merely releasing cultivated organisms. Limitations on stock abundance must be understood, and responsible protocols are needed to ensure success. For example, size of released organisms and when and where to release are critical considerations that affect survival of released fish. Acclimatization and behavioural conditioning may be needed to prevent severe mortality shortly after stocking.

Stock enhancement effectiveness depends on how well stocking is integrated with other management strategies. Stocking technology must be coupled with adequate regulations; it cannot effectively be used by itself as a strategy for managing fisheries targeting coastal stocks. In addition, lack of financial and human resources to enforce resource-management regulations remains one of the greatest problems in managing fisheries, with and without the use of stocking as an additional tool.

There is a need for fishing communities to work together to manage fished stocks. When hatchery releases are very effective at increasing fishery landings, stocking is also likely to increase fishing effort, which could result in overfishing of wild stocks unless there is a concerted effort to limit the take of wild individuals.

Although clear potential for success exists, the science of stock enhancement has not yet been developed enough to be widely implemented as a fishery management tool for catadromous and marine species. For example, after an extensive programme to evaluate stock enhancement and sea ranching potential in Norway, it is concluded that it is possible to increase the total population of some species (e.g. European lobster), but profitability has not yet been shown even for lobster, the most successful species tested.

To develop reliable stocking techniques, improvements in rearing technology and extensive testing through pilot release–recapture experiments are needed. There is a critical need for more science to advance the fields of aquaculture as well as the biology and ecology of stocked populations and interactions of hatchery and wild stocks.

Much will be learned about improving the efficiency of release strategies, as well as the life histories and management needs of wild stocks, if cultivated individuals are marked and released for experimental evaluation of stock enhancement potential. It is important to select a high-information content marking method. Better and smaller acoustic tags need to be developed, as well as smaller radio tags, to help managers and researchers gain a better understanding of fish movement patterns and harvest levels.

The economic aims for sea ranching activities must be evaluated over an extensive time frame needed to advance the technology. Only for Japanese flounder and beluga sturgeon has a clear economic advantage been shown from releasing cultivated juveniles. Improvements in survival during both the aquaculture and the release phases of the other case studies will be needed before conclusions can be drawn about the economic potential of those programmes.

KNOWLEDGE GAPS AND RESEARCH PRIORITIES INDICATED BY THE CASE STUDIES

- Interactions of stocked animals with wild stocks are the greatest concerns in coastal stocking programmes. Genetic diversity issues notwithstanding, the primary concern today regarding stocking programmes in coastal environments is whether stocked fish displace wild stocks or increase production. Given the intensity of the debate (e.g. Hilborn, 1998, 1999; Wertheimer *et al.*, 2001), this issue warrants serious scientific enquiry. Several of the case studies state that the stocked organisms had not displaced wild individuals but rather had added to production. However, the evidence is weak or not presented. Determining how many fish can be sustained in different habitats is a difficult research topic, but this is a critical issue for stocking programmes.
- Genetic interaction of stocked organisms with wild stocks is another hotly debated topic for which there is scant empirical evidence one way or the other (Campton, 1995). This topic has been emphasized in numerous symposia and publications. Yet there have been almost no attempts to evaluate empirically the effects of hatchery–wild genetic interactions on wild stocks. The Norwegian studies on this topic are some of the best available, as they have begun to examine actual effects of stocking on allele frequencies.
- There was no discussion of cannibalistic effects of stocked fish on wild fish. This issue is a clear topic for future evaluation by programmes releasing carnivorous organisms.
- Use of benign, high-information content tags is growing (e.g. Russell and Rimmer, this volume, with barramundi; Svåsand *et al.*, this volume, with European lobster). Their benign effects, and the large number of codes that are available for release–recapture experiments, make the coded-wire tags used in these studies ideal for resolving critical uncertainties in sea ranching. Coded-wire tags greatly facilitate development of optimal release strategies and adaptive management, as all experimental treatment conditions, controls and replicates can be coded in quite small organisms using these tags with minimal effects on animal performance.
- Many countries are working to develop genetic markers to identify hatchery stocks. Recent improvements in microsatellite DNA technology have opened the door to using genetic fingerprinting to identify different batches of hatchery fish. Genetic marks will provide a way to mass-mark batches of siblings affordably. However, genetic markers also have limitations. Because so many different tag codes are needed, it would be difficult to use genetic codes to perform, for example, simultaneous studies of release strategies such as size-at-release, release habitat and release season, as in Leber, Brennan and Arce (1998), Rimmer and Russell (1998), Russell and Rimmer (this volume) and Svåsand *et al.* (this

volume). In some of those studies, up to 80 different tag codes were used to batch-mark fish in a single experiment.

- In spite of the strong scientific approach used in the case studies, all listed critical uncertainties that need to be resolved. This topic is considered in both Munro and Bell (1987) and Leber (1999, 2002). For example, an experimental control for stocking effect is needed in studies to examine whether stocking actually increases production, instead of replacing wild fish. Simply comparing catch per unit effort (CPUE) before and after stocking is not sufficient because stocking effect is confounded by annual variability in fish abundance. What is needed to test stocking effect on abundance is a comparison of catch statistics at multiple sites with and without stocking.

SUGGESTIONS FOR A RESPONSIBLE APPROACH TO FUTURE STOCK ENHANCEMENT PROGRAMMES

There are several good summaries available of what is generally regarded today as a responsible approach to stock enhancement and sea ranching (e.g. Cowx, 1994; Blankenship and Leber, 1995; Munro and Bell, 1997). Many of the key issues are listed below.

Clearly, numerous critical uncertainties remain about how to design with confidence effective stocking programmes (Hilborn, 1999; Leber, 1999, 2002). Thus, a critical design aspect of any new stocking programme is to include at the outset a research component to evaluate ecological and economic potential to enhance a stock. Stocking programmes will continue to require an initial research phase until such time that clear protocols exist for how to ensure success, based on the body of evidence that will be gained from the development of scientific principles about stock enhancement.

It is also clear from the case studies here, and from history, that active adaptive management (Hilborn and Walters, 1992) needs to be incorporated into every stocking programme. When new questions are posed within the plans for every stocking event, new answers will become available to help guide subsequent stocking efforts. Thus, incorporating a modest research framework into stocking programmes will ensure that refinements are made constantly to improve the efficiency and effectiveness of stocking and to resolve critical uncertainties about stocking impact. Because of great uncertainty about the performance of stocking programmes, it is both economically and ecologically irresponsible to conduct stock enhancement and sea ranching programmes without a solid research framework (Hilborn, 1999; Leber 2002). Active adaptive management is the single most important measure that can be taken to improve the potential for success in existing stocking programmes.

Measures of success in new sea ranching programmes should include evaluation of key milestones at various stages of the development process (Blankenship and Leber, 1995). The various stages of development were described in several of the case studies presented here. To summarize, responsible stock enhancement and sea ranching programmes should gauge success at the following stages of development:

- Identify the priority target species.
- Identify the problems: what are the limiting factors to current fishery yields?
- Develop a management plan showing how stocking would be used within the context of other fishery-management strategies.
- Identify life history patterns.
- Identify genetic structure of target stocks and develop genetic protocols.
- Identify diseases and parasites of target stocks and develop high-health protocols.

- Identify risks and benefits of stocking.
- Identify critical uncertainties.
- Establish efficient aquaculture production technologies.
- Establish optimal release strategies (i.e. size at release, release habitat, release timing, release magnitude, conditioning and acclimatization, transport method, release distribution, marking method, adaptive management framework).
- Establish pilot-scale tests of enhancement potential.
- Identify release impact (hatchery contribution to fishery, recapture rate, whether there is a displacement effect, effect on genetic diversity of wild stock, net production effect, net effect on fishery yields, and contribution of spawning and recruitment to the next generation).
- Evaluate costs and values.
- Design and test a full-scale stocking programme.
- Use adaptive management to refine stocking strategies.

Fishery resources are rapidly declining in the face of an expanding human population. We must act now to resolve the critical uncertainties about stocking programmes. In the twenty-first century, the world will need increasingly effective new strategies for replenishing and sustaining world fisheries. We cannot afford to neglect the development of reliable stock enhancement and sea ranching technologies, if such techniques have the potential to help restore, augment and sustain viable fish populations. As the case studies here show, substantial potential exists if stock enhancement and sea ranching can be made more economical.

ACKNOWLEDGEMENTS

Many of the ideas expressed here are the product of discussions with Rich Lincoln, Conrad Mahnken, Ray Hilborn and members of the World Aquaculture Society Working Group on Marine Stock Enhancement. I thank FAO for their promotion of responsible stocking practices and for their work to expand current knowledge about recent developments in the field of stock enhancement.

References

Blankenship, H.L. & Leber, K.M. 1995. A responsible approach to marine stock enhancement. *Amer. Fish. Soc. Symp.*, 15: 167–175.

Blaxter, J.H.S. 2000. The enhancement of marine fish stocks. *Adv. Mar. Biol.*, 38: 1–54.

Campton, D.E. 1995. Genetic effects of hatchery fish on wild populations of Pacific salmon and steelhead: what do we really know? *Amer. Fish. Soc. Symp.*, 15: 337–353.

Cowx, I.G. 1994. Stocking strategies. *Fish. Manage. Ecol.*, 1: 15–30.

Hilborn, R. 1998. The economic performance of marine stock enhancement projects. *Bull. Mar. Sci.* 62(2): 661–674.

Hilborn, R. 1999. Confessions of a reformed hatchery basher. *Fisheries*, 24(5): 30–31.

Hilborn, R. & Walters, C.J. 1992. *Quantitative fisheries stock assessment*, New York and London, Chapman and Hall. 570 pp.

Honma, A. 1993. *Aquaculture in Japan*. Tokyo, Japan-FAO Association. 98 pp.

Leber, K.M. 2002. Advances in marine stock enhancement: shifting emphasis to theory and accountability. *In* R. Stickney & J. McVey, eds. *Responsible aquaculture*, pp. 79–90. Abingdon, UK, CABI.

Leber, K.M. 1999. Rationale for an experimental approach to stock enhancement. *In* B. R. Howell, E. Moksness & T. Svåsand, eds. *Stock enhancement and sea ranching*, pp. 63–75. Oxford, UK, Fishing News Books, Blackwell Science Ltd. 606 pp.

Leber, K.M., Brennan, N.P. & Arce, S.M. 1998. Recruitment patterns of cultured juvenile Pacific threadfin, *Polydactylus sexfilis* (Polynemidae), released along sandy marine shores in Hawaii. *Bull. Mar. Sci.*, 62(2): 389–408.

Munro, J.L. & Bell, J.D. 1997. Enhancement of marine fisheries resources. *Rev. Fish. Sci.*, 5(2): 185–222.

Platt, J.R. 1964. Strong inference. *Science*, 146: 347–353.

Rimmer, M.A. & Russell, D.J. 1998. Survival of stocked barramundi, *Lates calcarifer* (Block), in a coastal river system in far northern Queensland, Australia. *Bull. Mar. Sci.*, 62(2): 325–335.

Wertheimer, A.C., Smoker, W.W., Joyce, T.L. & Heard, W.R. 2001. Hatchery pink salmon in Prince William Sound: enhancement or replacement? *Trans. Amer. Fish. Soc.*, 13

With coastal fisheries in decline around the world, there is mounting concern about how long current sources of seafood can supply world needs. Governments, resource managers and those who make their livelihood from fishing are seeking better ways to improve fishing yields. Many seek greater emphasis on restocking and aquaculture-based stock enhancement as a way of rapidly replenishing depleted fish stocks and increasing fishery landings. This volume presents case studies that represent various scenarios and situations that use sea ranching and marine hatchery enhancement to generate income, re-establish fisheries and conserve aquatic biodiversity. The case studies include an integrated development programme for marine stocking in Norway; stock enhancement of barramundi in Australia for recreational fisheries; restocking sea cucumbers in Pacific Islands; sturgeon stocking programmes in the Caspian Sea with an emphasis on Iran; and an assessment of stocking effectiveness of flounder in Miyako Bay, Japan, through a fish market census. The studies demonstrate that stocking can clearly work in some cases to increase fishery landings, but that economic success will depend on many factors such as the management system, survival rates, culture costs and how the resource is valued. Sea ranching technologies and strategies need more scientific development before stocking can be generally accepted as an economically effective fishery management tool in coastal regions.

ISBN 92-5-104961-0 ISSN 0429-9345

9 789251 049617

TC/M/Y4783E/1/12.04/2100